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"Kinematics and Kinetics of the Pull Phase of Lifting"

Submitted by:

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A comparison was made between measured and modeled hand forces applied to the load during two handed floor to knuckle lifting tasks in the sagittal plane, to determine if dynamic biomechanical models should be supplemented with additional information to accurately model hand forces. For the middle portion of the lift, the carry phase, measured and modeled hand forces were comparable. They deviated substantially at the beginning of the lift, the pull phase, and at the ending, the placement phase, of the lift. A steep spike during the pull phase of the lift was exhibited by the measured hand forces which was not evident in the modeled hand forces. This peak force sometimes occurred just before liftoff. The peak compression and shear forces at the low back calculated with input of measured hand forces were greater than peak modeled low back forces for the normal, comfortable speed of lift, and significantly greater for the fast speed of lift. For most lifting tasks, the steep peak at the pull phase in compression and shear forces at the low back plotted over the duration of the lifting tasks was also evident. The authors conclude that the dynamic biomechanical model should be supplemented with a static model of the pull phase of the lift to more accurately represent the peaking of actual hand forces and the resulting compression and shear forces at the low back.

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CONTENTS

ABSTRACT

The purpose of this investigation was to compare measured and modeled hand forces applied to the load during two-handed floor-to-knuckle lifting tasks in the sagittal plane. The goal of this objective was to determine if dynamic biomechanical models should be supplemented with additional information to accurately model hand forces.

Hand force was measured with a strain gage instrumented apparatus which simulated a box-type container with handles. The measured hand forces were synchronized with video joint displacement data and load liftoff. Five male subjects performed lifting tasks for two experiments to determine the effects of speed of lifting motion, frequency of lift, percentage of maximum acceptable weight and weight of load on peak hand forces and resulting peak forces at the low-back. A dynamic biomechanical model was used to calculate hand forces and low-back forces.

Measured and modeled hand forces were comparable for the middle (carry) portion of the lift, but deviated substantially at the beginning (pull) and ending (placement) phases of the lift. The measured hand forces exhibited a steep spike during the pull phase of the lift which was not evident in the modeled hand forces. The peak magnitudes of the measured hand forces were significantly greater than the modeled values for all lifting tasks. The occurrence of peak measured hand forces was distributed about the liftoff, indicating that peak hand force occasionally occurred just before liftoff.

The peak compression and shear forces at the low-back calculated with input of measured hand forces were greater than peak modeled low-back forces for the normal, comfortable speed of lift, and significantly greater for the fast speed of lift. The steep peak at the pull phase in compression and shear forces at the low-back plotted over the duration of the lifting tasks was also evident for most lifting tasks.

The results of this investigation indicate that the dynamic biomechanical model should be supplemented with a static model of the pull phase of the lift to more accurately represent the peaking of actual hand forces and the resulting compression and shear forces at the low-back.

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CHAPTER I

INTRODUCTION

Back injuries account for one in every five injuries and illnesses in the workplace, with approximately one million workers suffering from back injuries in 1980 (Center for Disease Control [CDC], 1983). These back injuries are classified as musculoskeletal injuries which rank among the leading work-related diseases and injuries in the United States (CDC, 1983).

As such, back injuries are a large and costly problem for workers and their employers in terms of human suffering and economic cost, and low-back pain is industry's most expensive medical problem (Klein, Jensen, Sanderson, 1984; Vojtecky et al., 1987). Back strains/sprains, the largest subset of back injuries, produced an approximate direct compensation cost of at least 1 billion dollars in 1984, and general back injuries are the most frequent workers' compensation claim -- 1 of every 5 claims (Klein et al., 1984). Economic costs are also increased due to workers' lost time at work due to back injuries (an average of 14 days) and reduced productivity upon return to work because 40% of returning workers are assigned to light duties (Bureau of Labor Statistics [BLS], 1982).

In 1982, the Bureau of Labor Statistics reported that 75% of back injuries occurred while the victims were in the act of lifting. Of these lifting-associated back injuries, about 50% were injured when lifting from the floor. In 2/3 of the cases where the origin of lift was the floor, workers held or carried the load for less than one minute and in half of these cases, workers claimed that they did not carry the load through any horizontal distance while lifting.

The severe statistics regarding back injuries in industry have been noted since at least the early 1960s (Snook & Ciriello, 1972), and much research has been focused on reducing back injury in industry. One such focus is on the amount of load (lifting capacity) a person can handle without back injury. Lifting capacity may be evaluated by three methods: psychophysical, physiological and the biomechanical approaches. In the psychophysical approach, the person lifts as much weight as he/she believes can be safely handled. The physiological approach deals with cardiovascular capacity of the body during repetitive lifting. The biomechanical approach calculates internal and external forces developed on the body during lifting, and estimates the resulting deleterious forces on the spinal vertebrae. The selection of these evaluation approaches is determined by the characteristics of the lifting task. Traditionally, capacity of lifting tasks performed at slow frequency (.5 to 4 lifts/min) are limited by strength of the individual and analyzed by the biomechanical approach, and tasks performed at faster frequencies (greater than 4 lifts/min) are limited by the individual's cardiovascular endurance and analyzed by the physiological approach. In the biomechanical case, the forces estimated to be created on the spine during a specific lifting task are compared with compression forces determined experimentally to cause damage to the vertebrae. It is reasoned that if the forces on the spine are greater than the recommended limits of compression, the person performing the lifting task is at risk of back injury. Although lifting tasks performed at higher frequencies are usually analyzed with the physiological approach, this study concentrated on biomechanical analysis of floor-to-knuckle maximal and submaximal lifts performed at low and high frequencies of lift because it appears that forces produced on the spine which are calculated with consideration of applied hand forces during repetitive lifting tasks need to be examined.

Significance

Past lifting research has pinpointed the L5/S1 joint of the spine as the area of the body most significantly affected by developing compression and shear forces during a lifting motion (Morris, Lucas, & Bressler, 1961; Tichauer, 1971). Specifically, the L5/S1 intervertebral disc has been named as the injured or damaged part of the spine (Rowe, 1969). Biomechanical models have been developed and utilized to estimate compression and shear forces acting at the fifth lumbar and first sacral (L5/S1) vertebrae during lifting tasks. Data input for the biomechanical model is usually in the form of operator characteristics (i.e., strength and anthropometry), posture history (orientation of the joints throughout the lifting motion), and task information (distance from the object, height of lift, and weight of load). Output of the biomechanical model includes estimates of forces on the spine and may include time-histories of kinetic and kinematic information for each joint segment of the body. The model used in this study was Dynalift, a two-dimensional model for symmetric two-hand lifting developed by Ayoub, Chen and Coss (1986). This model was used to compare calculated external forces at the hand with measured forces applied by the hands to the box for a floor-to-knuckle height lift.

The National Institute of Occupational Safety and Health Lifting Guide (NIOSH, 1981, p. 40) states that "dynamic forces imparted by rapid or jerky motions can multiply the load's effect greatly," and recommends that manual materials handlers lift the load in a smooth and deliberate manner. However, it is suspected that the human operator must lift in a manner which causes peak forces to be applied by the hands to the load before it is accelerated, resulting from a jerking motion to overcome the inertia of the box resting on the ground. Therefore, smooth lifting may not be a realistic recommendation and past biomechanical estimations of compression and shear forces on the spine during lifting may have been underestimated, because of additional forces applied while the lifter is still in a static condition. Those few milliseconds when the individual is in the process of pulling up on the load, but before the box has left the ground, or immediately after lift-off could be extremely stressful to the low-back. The application of knowledge of the peak applied forces is useful for biomechanically reevaluating lifting tasks, and for establishing the point of time in the lift and associated posture when L5/S1 compression and shear forces truly limit lifting capacity.

Specific Aims

The lift may be described in three phases: (1) lift-off, or pull, (2) support and/or carry, and (3) lower and release. Despite the intensive past research about lifting, little is known about the forces applied to the load during the "pulling" stage of the lift, and the resulting compression forces at the L5/S1 during these moments. This study concentrated on the pulling phase of the lift, defined as the time period which begins with the application of external forces by the hands to the box being lifted and ends at the moment when the box departs from the floor, or when the external load at the hands has peaked.

The specific aims of the proposed research were:

1. To determine the maximum magnitudes in the horizontal and vertical directions of the external forces applied by the hands to the container during the pull phase of lifting from floor to knuckle height and compare these to biomechanical model predictions such as those obtained from Dynalift. Dynalift is an existing one muscle two-dimensional biomechanical model for two-handed symmetric lifting. The intent of this objective was to determine if dynamic biomechanical models, such as Dynalift (Ayoub, Chen & Coss, 1986) needed to be supplemented to reflect forces on the hands during the pull phase of lift, namely as the inertia of the load is picked up. This evaluation was made based on comparison of model results to direct measurement of the applied forces using a strain-gage instrumented apparatus with handles which simulated a box-type container.

2. To determine the effects of speed of lifting motion, frequency of lift, percentage of maximal acceptable weight of lift (%MAWL) and weight of load on the external forces applied by the hands to the container during the pull phase of lifting from floor to knuckle height. Subjects lifted increments of weight using normal and fast movements at three

frequencies of lift. Blocked factorial statistical analyses determined the effects of weight, percentage of maximum weight of lift (%MAWL), speed of lift and frequency of lift on the peak forces applied during the pull phase.

3. To determine the physical posture associated with maximum external forces applied by the hands on the container during the initial phase of lifting from floor to knuckle height and the location of the box when these peak forces occur. The analysis also determined when during the pull phase the posture associated with the peak applied forces occurred.

4. The final goal was to utilize a biomechanical model to estimate compression on the spine during application of the peak force during the pull phase of lifting.

Hypotheses

The following hypotheses were postulated for the study:

1. Faster speeds of lifting motions create higher peak vertical and horizontal forces applied to the handles to lift the box off the floor, compared to the peak forces applied to the handles to lift the box off the floor for slow speeds when lifting the same loads.

2. The weight of load (5 increments ranging from 6.24 kg to 24.77 kg) has an effect on the peak vertical and horizontal forces applied to the handles during the pull phase.

3. The peak vertical and horizontal forces generated while lifting a box loaded with 35, 60, and 85% MAWL vary for normal and fast speeds of lift.

4. Vertical and horizontal reaction forces at the hands calculated using the Dynalift biomechanical model are lower than those directly measured at the pull phase of lift.

5. Compression and shear forces at L5/S1 calculated using the Dynalift biomechanical model are lower than those calculated when using measured reaction forces at the hands as direct input to the biomechanical model.

6. Peak applied vertical and horizontal forces by the hands and peak L5/S1 compression and shear forces actually occur very close to the moment of liftoff (immediately before, immediately after, or during).

CHAPTER II

REVIEW OF LITERATURE

The review of literature summarizes research regarding lifting, especially the initial phase of the lift, called the pull or lift-off. Research reported regarding the biomechanical approach to lifting analysis emphasizes kinematics and kinetics involved in the lifting motion. Those biomechanics investigations which study occupational lifting primarily analyze the lifting motion with the use of a biomechanical model which estimates forces created on the body, and compares these with safety limits. Other biomechanics investigations on sports lifting describe kinematics and kinetics characteristics of the lift.

Anatomy of the Spine

The human vertebral column is composed of 33 vertebrae (7 cervical, 12 thoracic, 5 lumbar, 5 sacral and 4 coccygeal) and the function of the vertebral column is to provide support and protection for the spinal cord. The lumbar vertebrae are the most massive of the spinal vertebrae, and are characterized by the long length of the transverse processes and the long sagittal length of the spinous process. The five sacral vertebra are fused to form a single bone which articulates with the pelvic girdle.

Each cervical, thoracic and lumbar vertebra is separated by an intervertebral disc which functions to provide flexibility and cushioning of the spine. The disc is composed of an outer fibrous part, the annulus fibrosus, which surrounds a central gelatinous mass, the nucleus pulposus. The annulus fibrosus functions to resist axial tensile stresses and the nucleus pulposus transfers the applied forces away from the center of the disc (Chaffin and Anderson, 1984). Each of the articulating surfaces of these vertebrae is lined with cartilage endplates which sandwich the intervertebral disc.

Force Tolerance of the Spine

Since the disc appears to be the source of the problem underlying low-back pain, stress on the spine is usually determined by the amount of force required to damage the intervertebral disc and cartilage endplates. Maximum tolerances of compression forces are determined experimentally with tests on cadaver vertebral columns. The tolerance of the human spine to withstand axial compressive forces varies widely according to age, gender, and health history. Data from several studies (Brinckmann et al., 1988; Evans, 1959; Jager, 1987; Sonoda, 1962) show that forces which cause microfractures in the cartilage endplates were 6.6 kN (675 kg) for males 40 years of age and younger, and 2.4 kN (250 kg) for males 60 years of age and older. However, these studies have reported a range of compression tolerance from 2.1 kN to 12 kN. Due to the smaller force-bearing area of the vertebral bodies of the female vertebra, it is estimated that compression tolerance is 17% less than that of the male (Sonoda, 1962).

Jager and Luttman (1989) summarized several studies of the compression strengths of various spine elements. They report that for 16 of these studies, N=307, the mean compressive strength of the spinal elements is 4.36 kN with a standard deviation of 1.88 kN. Variables which affect the measured strength include: preparation method of specimen, sex, age, diet and occupational activity of the person.

The effects of compression on the spine can be observed when the body has been loaded in a standing position, indicating that the discs are sensitive to axial load bearing. In fact, many researchers (Eklund & Corlett, 1984; Fitzgerald, 1972; Kramer & Gritz, 1980) have demonstrated actual decrease in body stature due to shrinking of the disc heights resulting from loading of the body weight while standing. The shrinkage of the discs due to compression is an important side effect of loading, since this shrinkage results from fluids being squeezed from the disc, adversely affecting the dynamic buffering capability of the disc for the bony surfaces of the vertebrae.

Shear forces applied to the lower vertebral column are resisted by posterior facet joints of the vertebrae and the annulus fibrosus of the intervertebral discs. Farfan (1970) recommended the failure limit of the articular facets of the lumbar vertebrae to be no greater than 1.735 kN shear force.

It must be noted that these tolerance limits have been determined in static tests. The NIOSH (1981, p. 36) lifting guide reports that:

> based on the industrial study of 400 workers it is apparent that jobs which place more than 650 kg (6.4 kN) compressive force on the spine are hazardous to all but the healthiest of workers. In terms of a specification for design, a much lower level of 350 kg (3.43 kN) or lower should be viewed as an upper limit.

However, the usefulness of these guidelines determined by static methods may be dubious since most low-back problems have been shown to be caused by chronic exposure to stresses induced by dynamic lifting, rather than one traumatic lifting accident during slow, maximal lifting (NIOSH, 1981). It has been shown that compressive strength of the spine is significantly lower under conditions of repeated loading (NIOSH, 1981). Since little is presently known about fatigue fracture of the spine, repetitive lifting (faster than .2 lifts per minute) limits based on biomechanical criteria have not been established. Rather, limits for frequent lifting have been determined by the physiological approach, based on the cardiovascular endurance of the lifter, and biomechanical limits of repetitive lifting have been ignored. A new approach to repetitive lifting limits analysis is required which would consider biomechanical stresses, submaximal as well as maximal, which appear to stress the lifter biomechanically as well as physiologically during fast lifting.

Low-Back Pain and Injury

Rowe (1969) estimated that 70 to 80% of all chronic back pain was due to repeated stress on the spine. The location of the pain source appears to be the vertebral joints of the lower lumbar spine (L4/L5) and the upper sacral spine (L5/S1) in 90% of all back injuries

(Armstrong, 1965; Morris et al. 1961; Tichauer, 1971). There are many theories as to the etiology of low-back pain caused by lifting. Park and Chaffin (1974) summarized them as follows: muscle uncoordination in fast lifting motions, muscular fatigue with repeated lifting exertions, and cumulative disc degeneration due to high repeated disc compression forces created during lifting. According to the discussion on compression tolerance of the spine, the forces required to initiate disc degeneration do not have to be "high," as described by Park and Chaffin (1974), but applied repetitively. Presently, it seems that the disc degeneration theory is most accepted of the theories, since incidence rates for low-back pain are related to repeated compressive forces on the L5/S1 disc which are known to eventually result in disc degeneration. Degeneration is signified by microfracturing of the cartilage endplates, and loss of fluid from the intervertebral disc.

Stress on the low back is due to the weight lifted, weight of the lifter and the method of lifting. The danger of lifting is that low mechanical advantage of the muscles due to the small moment arms in comparison to the moment arm of the load produce high stresses at the low back in certain body postures even when lifting light loads. Therefore it is important to estimate the stresses imposed on the low back during the lifting task to determine if the lifter is at risk of injury while performing the task. Biomechanical modeling serves this purpose.

Biomechanical Models

Numerous biomechanical models have been developed to estimate spinal stress on the lower back created during the lifting motion (Ayoub et al., 1974; Ayoub & El-Bassoussi, 1978; Chaffin & Baker, 1970; Frievalds et al., 1984; Park & Chaffin, 1974). Functions of biomechanical models include the simulation of the capacities of the muscles to develop required strength at each of the joints, postural stability of the body and compressive or shear forces on the spine. Factors which affect the biomechanical evaluation of the load are: load dimensions and stability, horizontal and vertical location of the load, lifting posture, foot traction, adequacy of grip, obstructions, space constraints, speed and frequency of lift.

Biomechanical models have been developed on both static and dynamic principles. Static models do not account for inertial forces and inertial torques at the segment center of mass due to acceleration of the segment during body movement. Static models therefore tend to underestimate compressive forces on the spine during the load acceleration phase of the lift, and in fact, several researchers have demonstrated that accounting for dynamic effects (inertia contribution to resultant forces and moments) significantly increases predicted forces and moments (Ayoub et al., 1974; Bush-Joseph et al., 1988; Frievalds et al., 1984; Garg et al., 1982; Hall, 1985; Jager & Luttman, 1989; Leskinen et al., 1983; McGill & Norman, 1985; Smith et al., 1982; Troup et al., 1983). The primary difference between static and dynamic application depends on the acceleration of the body during the lift. For lifts performed at very slow speeds acceleration is negligible and they are approximated by static models. Although static models may be appropriate for very slow lifting or holding/carrying posture analysis, they are inappropriate for biomechanical analysis of repetitive lifting due to the speed of the lifting motion. McGill and Norman (1985) recommend that the most conservative estimate of L5/S1 compression of the static and dynamic analyses be used to determine the risk of a specific lifting task. Dynamic models have evolved from static models and account for forces due to speed and movement of the body parts.

The static and dynamic models reviewed here share common basic assumptions as summarized by Winter (1979, p. 66).

(1) Each segment has a fixed mass located as a point mass as its center of gravity;

(2) The location of each center of mass remains fixed during movement;

(3) The joints are considered to be hinge (pin) joints;

(4) The mass moment of inertia of each segment about its mass center (or about either proximal or distal joints) is constant during the movement.

Generally, these models predict only those forces which result after the load is in motion, since they do not account for forces being applied to the load before this time. Except where specified, models reviewed in this chapter are two-dimensional analyses of two-hand symmetric lifting in the sagittal plane. In several instances these models were developed and then utilized to perform an experiment regarding moments and compressive forces resulting from various factors. Where this is the case, the model and results relevant to the proposed research are described.

Chaffin and other researchers (Chaffin & Baker, 1970; Martin & Chaffin, 1972; Park & Chaffin, 1974) developed a static biomechanical model which evaluates the lifting capacity by comparing estimated moments produced at the joint articulations during the lifting motion, with the measured maximum voluntary strength of the lifter. The earlier models were static models only, neither accounting for acceleration of the load nor acceleration of the body segments of the lifter. This model was developed only for nonrepetitive, short-duration lifting tasks of frequencies .2 lifts/minute or less. Strength capacity estimated to be necessary to hold a weight was determined based on the configuration of the posture, and then the maximum possible weight which could be held was predicted. The original model (Chaffin & Baker, 1970) has been modified into a quasi-static model (Park & Chaffin, 1974) which accounts for acceleration of the load, but not inertial forces acting on the body segments. This model was used to analyze the initial lifting posture because of the suspected high spinal stresses in this position due to initial high acceleration required to move the load and the long moment arm between the load and L5/S1. The seven-link model included effects of abdominal pressure and compressive forces due to the erector spinae. Initial acceleration of the load was estimated as the average of the acceleration of the first 100 msec of the lift. This model was used to compare three postures holding a load which produced 1274 lb of compressive force on the L5/S1. The authors concluded that utilizing a lifting posture with a stooped back minimizes compressive stress to the low back, if the load cannot be straddled and lifted through the knees.

Anderson et al. (1985) developed a static biomechanical model for sagittal plane lifts which estimated the following parameters: strain in the ligaments posterior to the lumbosacral joint center-of-rotation, the moment generation requirement of the trunk erector musculature, compression on the sacral endplate and strain in the posterior aspect of the outermost layer of the annulus. Moment calculations in the model accounted for moments due to abdominal pressure, ligament strain, muscles and disc resistance to bending. These moments were called the restorative extensor moments which opposed the moments created by the load in the hands and body weight above L5/S1. The model contains equations which predicted the orientation of the L5 and S1 vertebrae according to torso and knee angles. The predictions showed that torso flexion beyond 30^o is accomplished mainly by hip rotation, and flexion to 30^o occurs in the lumbar spine. The compression and shear forces on the sacral endplate were the summation of the forces due to load on the hands, body weight above L5/S1, abdominal pressure (for compressive force only -- not shear force), ligament strain and muscle (erector spinae) contraction.

The model first predicts the L5/S1 orientation and then the intra-abdominal pressure restorative moment about L5/S1. Following these steps the moments due to ligament resistance and muscle contraction are calculated and these are then used to determine the strain on the posterior annulus. The two methods of model validation were: (1) comparison of predicted and observed stress/strain values and (2) investigation of ligament, posterior annulus strains, erector spinae muscle moment requirements and disc compressive loads for various postures and loads. Results of the first validation study showed that the articular ligament sustained 100 to 130% of its maximal possible strain, which according to the authors, does not adversely affect the other predictions. Results of the second validation study were:

(1) Strain of the posterior annulus increased with torso flexion , but does not exceed 2.7% and strain also increased significantly with load. However, strain was below the elastic limit of 31.5±1.8%; therefore it is probable that endplates would fracture before the annulus gives way.

(2) For a 500 N load, approximately 20% of the male and 60% of the female populations could not provide the required trunk extensor moment at a torso angle of 60^{o}.

(3) Disc compression increased as the trunk was flexed and also as the load at the hands increased. At less than 30^{o} of trunk flexion the effects of body weight and load have major contributions to disc compression, but at greater than 30^{o} flexion, muscle contraction is the major contributor. Abdominal pressure offsets not more than 10% of the compressive force. As the load was increased from 0 to 500 N (0 to 51.02 kg) the disc compressive force increased from 2200 to 5400 N (224 to 551 kg) which is well above the 3425 N (350 kg) recommendation by NIOSH for reduction of low-back pain risks.

Dynamic Models

El-Bassoussi (1974) and Ayoub and El-Bassoussi (1976) developed a two-dimensional dynamic lifting model which accounted for inertial forces and accelerations of the segments. This model was a six-link system: hand, lower arm, upper arm, trunk, upper leg and lower leg. The trunk was further divided into three parts: hip joint to center of L5/S1, L5/S1 to center of L4/L5, and L4/L5 to the shoulder joint. Displacement, velocity and acceleration were calculated by using the Slote and Stone (1963) algorithms. Considerations for pelvic rotation, intra-abdominal pressure and forces of the erector spinae were built into the model.

Ayoub and El-Bassoussi (1976) then used the model to determine the relationship between biomechanical lifting equivalents of two types of lifts (back and leg) and compression forces created on the spine during these lifts. It was found that back lifts produced higher compressive forces on the spine than did leg lifts for the same biomechanical equivalents and that the maximum compressive forces of each lift occurred within the first quarter of the total lifting time. Postures which were associated with maximum compressive forces of the spine were those where the load was just being picked up. This was the case when the load moment arm was the longest.

El-Bassoussi (1974) concluded that the net torque of the hip is principally responsible for the compressive forces generated on the spine, and that the abdominal forces create a moment which aids the spine in carrying the load. For the same biomechanical lifting equivalents, back lifting produced greater maximum net torques on the hip and estimated compressive forces than the leg lifting method. Maximum compressive forces on the spine were positively linearly related to the biomechanical lifting equivalents and directly proportional to net hip torque.

Leskinen, Stalhammar and Kurorinka (1983) performed two-dimensional dynamic analysis of spinal compression on four different lifting techniques using a two-link model. The first segment was the arms and the second segment was the trunk above the L5/S1, including the neck and head. A compression force was added due to the muscle force of the erector spinae based on the torque about the L5/S1, but development of intra-abdominal pressure was not accounted for. Twenty male subjects performed two lifts for each of the four lifting styles with a 15 kg load. The load was lifted from 10 cm above the ground to knuckle height. The four types of lifts were the leg lift, back lift, trunk kinetic lift and load kinetic lift. The subjects were trained to perform each type of lift in 2.5 sec.

Data collection included x-y coordinates vs time of the knuckle of the middle finger, shoulder, hip and ankle; x and y accelerations of the load and ground reaction forces at the feet. All data were sampled at 100 Hz. Force on the load was derived from acceleration of the load. Each lift was compared with each of the other three lifts with a paired t-test on the following variables: peak vertical velocity of load, peak force at the feet, force x time integral at the feet, peak spinal compression and compression x time integral. Briefly, the results are as follows: (1) mean peak velocities for each of the four lifts were not significantly different and ranged from 1.25 to 1.29 m/s; (2) leg lifting produced 362 N of peak inertial force at the feet, which was significantly greater than the three other lifting styles; (3) back lifting produced a mean of 61.6 Ns inertial force x time integral at the feet, significantly less than that of the other three types of lift; and (4) trunk kinetic lifting (mean = 6629 N) followed by back lifting (6365 N) created the highest peak compression at the L5/S1, with trunk kinetic lifting compressive force significantly greater than that created during leg lifting and leg kinetic lifting. In summary, leg lifting produced least stress in terms of peak spinal compression, while the back lift was associated with the greatest stress over the entire lift and the trunk kinetic lift was classified as the most highly stressful of the lifting methods. Times of occurrence of peak velocities, peak compression at L5/S1 and peak forces were not reported.

Troup et al. (1983) attempted to determine the relationship between intraabdominal pressure (IAP) and lumbosacral stress during dynamic lifting with the same model as Leskinen et al. (1983). Ten male subjects lifted or lowered a 15 kg box from floor to knuckle height using six lifting techniques: back lift, leg lift, load kinetic lift, trunk kinetic lift, forward kinetic lift and two-stage leg lift. Strain gages were fitted on the handle of the box to directly measure applied forces, the IAP was recorded by radio signals from a swallowed pill and joint kinematic data was recorded by filming. IAP was compared with peak vertical velocity of load, peak lumbosacral compression, integral of lumbosacral compression over time, and peak hip torque by paired t-tests.

The two-segment model accounted for external vertical and horizontal forces applied by the hands to the load, internal forces and torques caused by gravity, and horizontal, vertical and angular accelerations acting on the body segments. As in the Leskinen et al. (1983) study, tensile force in the erector spinae was calculated to balance torque at L5/S1 and combined with gravitational and inertial forces to estimate lumbosacral compression. The authors list the following results (p. 525): (1) lifting was executed faster than lowering; (2) peak hip torques were greater when the trunk was flexed than when the knees were flexed; (3) peak L5/S1 compressions were substantially higher for lifting than for lowering; (4) peak compression and hip torques did not always occur together in all techniques. The length of the lever arm creates high hip torques in techniques that require trunk flexion; (5) IAPs were less when the trunk was flexed than when the trunk was erect; and (6) there was no definite pattern to explain the IAP relationship to the named parameters. The authors did not report the points in time when the parameters occurred during the lifting movement.

Frievalds et al. (1984) developed a seven-link dynamic model of lifting and then utilized it to determine the effects of box size on compressive loads on the spine. Four box sizes were used, three of the boxes had handles and one did not. Consideration of the dynamic effects of the lift (overcoming initial moments of inertia, acceleration and deceleration) increased vertical ground reaction force and L5/S1 compressive forces. The dynamic effects increased the static load by 40% of its weight. The rise in vertical ground reaction forces corresponded to the effect of the accelerating load and then forces decreased and levelled off at the value equivalent to the subject's weight plus the load. Vertical ground reaction forces peaked 400 msec after the load left the floor. Frievalds indicated that the compressive forces on the spine are oscillatory possibly due to a parabolic lifting trajectory in which the long moment arm from the L5/S1 to the load decreases as the load is picked up and then increases as the box is placed at its destination. Higher compression forces were not necessarily caused by larger box sizes, since less load was selected by the subjects for the larger boxes. Frievalds also found that boxes without handles resulted in less compressive forces than boxes with handles, but boxes with handles had a faster rise time and higher peak ground reaction forces. He concluded that although handles should provide coupling, the subjects were more cautious in lifting the boxes without handles and thus developed less compressive forces on the spine.

McGill and Norman (1985) developed a six segment dynamic model to analyze two-dimensional symmetric two-hand lifting in the sagittal plane. The six segments were the load/hands, forearm, upper arm, head-neck, thorax/abdomen and pelvis. Joint locations were marked and recorded on 16 mm film at 80 Hz. Vertical forces applied to the load by the hands were derived from data collected with an LVDT mounted on the lifting jig. Four subjects performed a task which involved lifting an 18 kg sheet metal load from the back of a table (a reach of .83 m) and brought to rest against the worker's abdomen.

Dynamic, static and quasi-dynamic analyses were performed. Subjects produced consistent lumbar (L4/L5) moments for each of the three analysis methods, and forces applied by the hands. Their results indicate that the vertical force applied by hands showed a negative force on the hands prior to the load being lifted from the pallet. This negative force was attributed to a pushoff on the load by the subject to aid in spine extension and to supply the trunk with angular momentum. With regard to differences in results of the three analysis methods, the static model peak L4/L5 moment was on the average 84% of the dynamic model moment, and the quasidynamic model overestimated the full dynamic model peak L4/L5 moment by an average of 25%. However, not all trials resulted in larger dynamically determined moments than statically determined moments. The authors hypothesize that this may be due to varying acceleration profiles or momentum transferred to the load from the upper trunk and limbs. Grieve (1975) observed that angular velocity of the upper body prior to weight acceptance decreased upon the loading jerk. Also, McGill and Norman reported that variability in the resultant moments prior to lift-off could be explained in terms of the forces produced at the hands.

Jager and Luttman (1989) developed a three-dimensional 19-segment dynamic model to simulate both symmetric lifting in the sagittal plane and nonsymmetric lifting. The model predicts both static and dynamic loads on five areas of the lumbar spine. Considerations for eight trunk muscles and intra-abdominal pressure are included in the model. The authors then used their model to determine the effects of several factors on the load created on the lumbar spine. Their conclusions with respect to inclination of the trunk and location of the load were: lower compressive force was created when the trunk was only slightly inclined than when the trunk was inclined at 90 degrees (bent over), and arm positions which allow the load to be moved close to the body cause less compressive force than those positions which hold the load away from the body.

Velocity of lift was also investigated, in which the lift action was simulated to be completed in 2, 1.5 and 1 sec. Dynamic analyses of the back lifts with 0, 20 and 40 kg loads were compared with the corresponding static analyses. Included in this analysis were two assumptions: (1) load and all body parts are at rest at the beginning and end of the lift, and (2) body parts and load are accelerated during the first half of the movement and deccelerated during the second half. Three acceleration and deceleration periods were simulated at 1, 0.75 and 0.5 sec each. Analysis showed that static and dynamic differences increased with increases in load weight. Static analysis underestimated compression at the beginning of the lift. Consideration of the dynamic effects showed greater difference at the beginning of the lift where acceleration was accounted for, and showed that overestimation of compression occurred toward the end of the lift where deceleration is accounted for which decreases forces on the lumbar spine.

The influence of the initial jerk movement, required to pull the load from the floor, on compressive forces was simulated by manipulating the acceleration phase of the lift 0.75, 0.5, 0.3 and 0.1 sec. Acceleration periods faster than 0.75 sec caused the compression force vs time profile to exhibit two peaks, instead of one, showing effects of inertia at high acceleration rates. The authors called the 0.1 sec acceleration duration lift a jerky lift and noted that the compression forces were approximately double those estimated without considering the jerk. The researchers also compared the forces developed at the L5/S1 with those at the L1/L2. The differences in forces between these areas were greatest near the beginning of the lifting movement, the force at L5/S1 estimated to be 1.5 times greater as the load is picked up from the ground.

Lifting Angle

Several researchers have reported that when lifting from the floor a person pulls the load toward the body (Ayoub & El-Bassoussi, 1976; Baumann et al., 1988; Chaffin et al., 1967; Frievalds et al., 1984; Garg et al., 1980; Garg et al., 1983; Park & Chaffin, 1974). Garg et al. (1983) used a static model to assess the effects of lifting angle on biomechanical stresses to the musculoskeletal system of the lower back. Using the psychophysical approach, subjects lifted four sizes of boxes from the floor to .81 m using free-style and squat methods of lifting. It was found that the subjects pulled the load toward the body when lifting and that the angle of pull increased with box width. The lift angle was greater for free-style vs squat lift and resulted in decreased moments at the elbow, shoulder, L5/S1 disc, and hips and an increase in moment at the knees and ankles. The estimated compressive force on the lumbar spine was 11% lower for lifting at an angle as compared to lifting the load straight up vertically.

Park and Chaffin (1974) estimated that the horizontal component of initial acceleration of the load ranged from .07 g to .22 g depending on the location of the load. Garg et al. (1980) have offered a biomechanical rationale for pulling the load toward the body. In summary, the moments produced by the horizontal component of the force actually assist the individual lifting a load by opposing moments produced by the vertical force component. The primary effect of pulling the load toward the body is to transfer stress from the arms and torso to the legs which have stronger muscles. The final result of pulling the load toward the body is that compressive force on the L5/S1 disc is reduced. This rationale has been successfully applied by competitors of snatch lifting, who have recently utilized a new method of lifting which involves pulling the barbell more toward the body during the first pull (Baumann et al., 1988).

The Pull or Lift-off

There are several diverse lifting activities ranging from manual materials handling to weightlifting competition. Included in these activities are floor-to-knuckle lifts performed on the job and competitive lifts such as the snatch, clean and jerk and dead lifts. While research regarding these lifts tends to focus on force prediction for occupational lifting tasks, and technique for competitive weightlifting, the common theme of the lift ties these studies together. Regardless of type of lift, the moment of lift-off, and immediately before and after it, have been repeatedly identified as important: from both the lifting technique and force production on the spine viewpoints.

Admittedly, competitive powerlifting and occupational lifting are different in many ways. The power lifter is attempting a one-time maximum, and usually applies the force impulse as quickly as possible making the moment of maximum forces as short in duration as possible. The power lifter is also highly coached in technique, such as when to extend the knees, etc. On the other hand, industrial workers may lift several loads per day at a submaximal or possibly maximal effort. However, for all types of lifts originating from the floor the initial pull of the load from the ground may be the limiting factor of a successful performance. In fact, the initial impulse of force applied in pulling the load is needed in power lifting to accelerate the load to the weaker upper body (Brown & Abani, 1985; Garhammer, 1982; Lander et al., 1985;). Garhammer (1980) stated that during the pull of competitive weightlifting the arms function only as cables, transferring the forces developed in the lower body to the upper body and then to the barbell. Lander et al. (1985) observed that where this initial impulse was not sufficient the load was lifted successfully only to the middle of the lift and then the remainder of the lift failed.

Another type of lift similar to those already described above is the isoinertial lifting test recommended by several researchers (Ayoub et al., 1980; Jiang, 1984; Kroemer, 1983) as a valid predictor of occupational lifting capacity. For this test increments of weight are lifted in three phases (Bryant et al., in press): the pull up to the waist, the change over on the handle to reorient the grip, and then the push up to 6 feet in height. Bryant et al. (in press) and Stevenson et al. (in press) investigated the dynamic factors of the isoinertial lifting test: displacement, velocity, acceleration/force and power. They found that peak acceleration of the weight and force applied to the handles occurred within 0.07 seconds after lift-off, and maximum power and velocity were generated during the first 28% of the total lifting time. The fast development of dynamic variables after lift-off has been reported by many investigators, for example: (1) Frievalds et al. (1984) found that vertical reaction forces recorded on a force platform during floor-to-knuckle lift reached peak values within 400 msec after lift-off; (2) Ayoub and El-Bassoussi (1976) reported maximum compression forces on the spine occurred within the first 25% of total lifting time during the floor-to-knuckle lift; (3) Garhammer (1980) reported that powerlifters had completed 86 to 94% of the work done for the entire lift from lift-off to maximum velocity of the barbell in the first 0.64 to 0.92 sec of the lift; and (4) Brown and Abani (1985) found that subjects performing the dead lift maximally accelerated the bar within 0.4 sec after lift-off.

In their study on incremental isoinertial lifting Bryant et al. (in press) and Stevenson et al. (in press) performed factor analyses on several lift parameters (displacement, velocity, acceleration/force and power during the following events: total time of lift; maximum and minimum velocity; maximum, 2nd maximum and minimum force/acceleration; and maximum and minimum power). The analyses revealed that technique variables such as when to apply force and power make as great a contribution to the success of the lifting performance as the magnitudes of the force and power applied. It appears that many powerlifters and their coaches would agree on this.

In general, it is accurate to say that lifting activities originating from the floor begin with a powerful pull to overcome the inertia of the load, and then, depending on the goal of the lift, provide acceleration of the load upward to aid the weaker upper body parts in handling the load. This apparently necessary initial pull is essentially a jerk motion applied to the load while it is on the floor. Interestingly enough, smooth and continuous lifting motions are recommended for both occupational lifting (NIOSH, 1981) and even for powerlifting (Brown & Abani, 1985). Bryant et al. (in press) also commented on the smooth and continuous lifting technique recommended by NIOSH (1981) by saying that it is inconsistent with the fast, powerful pulling motion which is required for a successful isoinertial lift.

CHAPTER III

RESEARCH PROCEDURE

The experimentation was executed in four phases. During Phase I, the subjects were recruited and familiarized with the lifting experiment. The subjects then determined their maximum acceptable weight of lift (MAWL) for the lifting frequencies during Phase II. In Phase III, data were collected as the subjects lifted increments of weight not to exceed the MAWLs determined in Phase II. Data were collected in the form of forces applied to the handles of the container and video information of joint center and container center of mass (c.m.) locations during the lifting activity. Phase IV involved utilization of a biomechanical model to calculate reaction forces of the hands and compression forces at L5/S1.

Phase I

Recruitment of Subjects

Five male students were recruited from Texas Tech University to participate in the experiment as paid volunteers. After being informed of the experimental procedures, the subjects gave written consent to participate in the experiment. All subjects passed a physical examination at the Texas Tech Health Science Center and were in good physical health with no past history of back disorders or injuries, or other ailments. Examples of the subject medical history forms and consent forms are shown in Appendix A. Age range of the subjects was restricted between 18 and 30 years.

Lifting Speeds

The lifting speed refers to the actual speed of the lifting motion. The lifting frequency is the number of times a lift is executed in one minute. The subjects lifted at two speeds, normal and fast, within each of the three frequencies of lifting (1,4 and 8 lifts per minute). The normal speed was the speed at which the subject performed the lifting motion without external cues regarding speed of lift. The normal speed was really the "natural" speed at which the subject tended to perform the lifting motion. The subjects were also instructed to lift the load as quickly as they could, causing them to lift at the fast speed. MAWL was determined for the normal lifting speed; subjects lifted from 35 to 85% MAWL for the normal and fast lifting speeds.

Familiarization Period

Each subject participated in a familiarization period consisting of a two-day, two hour per day program. The familiarization period was designed to acquaint subjects with the method of psychophysical determination of weight, and to practice the desired freestyle lifting technique. The freestyle technique is defined as that method of lifting which the subject feels is most suitable for the lifting task (Garg, Chaffin, & Frievalds, 1982). The subjects practiced selecting their maximum acceptable weight of lift (MAWL) for each of the three lifting frequencies at their normal lifting speed. The duration of adjustment period for practice at each lifting frequency was 40 minutes. This familiarization period was not aimed to increase muscular strength of the subjects. On the familiarization days the subjects practiced lifting at specified frequencies for 40 minutes; the initial 20 minutes of each familiarization day was reserved for instructions and anthropometric measurements.

The following anthropometric measurements were collected during Phase I using the same protocol as Ayoub et al. (1980): stature, weight, hand-forearm length, upper-arm length, trunk length, upper-leg length, lower-leg length and abdominal depth.

Phase II

Determination of MAWL

During this phase the upper limits of weights which were lifted in Phase III were determined for each subject. The MAWL was determined for each subject at the normal lifting speed using the psychophysical approach. The subjects were asked to lift the container from floor to knuckle height. Two determinations of the MAWL were conducted at each frequency; one with a heavy initial load and the other with a light initial load. The starting weight was randomly selected to be either relatively heavy (approximately 80 lb) or relatively light (approximately 10 lb) (Legg and Myles, 1981). The subjects were asked to adjust the weight in the container to an acceptable level which they felt they could lift over an eight hour workday at that frequency by adding or removing some weight from the load already in the box. Lead weights were of irregular shapes and sizes to reduce the subject's knowledge of the amount of weight added or subtracted from the container. The subjects were encouraged to make as many adjustments as they desired, but no external motivation was provided such as encouragement to lift more or reference made to the effect that the individual was performing better or worse than an arbitrary reference value (Mital, 1983; Ayoub, et al., 1978). The subjects were instructed to "work as hard as they can without straining themselves, without becoming unusually tired, weakened, overheated or out of breath" (Snook, 1978). Lifting instructions were pre-recorded on cassette tape and played to each subject to ensure consistency of instructions between the subjects. Sixty minutes were allowed for each adjustment period and if the final weight at the end of second period was within 15% of the final weight of the first period, then the average of these final weights was recorded as the MAWL. If this was not the case, then both adjustment periods were repeated at a later time until the 15% criterion was satisfied (Snook and Ciriello, 1974). Fernandez (1986) reported that most weight adjustment using the psychophysical approach occurred within the first hour of the eight hour experimental period, therefore it was felt that 60 minutes was an adequate adjustment period for this study.

Phase III

Phase III was conducted using two experiments. The first experiment investigated the effects of %MAWL, speed of lift and frequency of lift on peak hand forces. The second experiment investigated the effects of weight increments and lifting speed on the peak hand forces while lifting at 1 lift per minute.

Experiment 1: Speed, Frequency and %MAWL Effects

Experiment 1 investigated the effects of %MAWL, speed of lift and lifting frequency on the response variables. The independent variables for this experiment were %MAWL, lifting speed and lifting frequency. The levels of %MAWL were 35, 60, and 85% MAWL. The levels of lifting speed were normal and fast. The levels of frequency were 1, 4 and 8 lifts per minute. The experimental design was a split-split plot factorial blocked on subjects with two samples per cell; this design is illustrated in Figure 1. The whole-plot variable was lifting speed. The split-plot variable was lifting frequency. The split-split-plot variable was %MAWL.

The subjects lifted the container which contained a %MAWL ranging from 35% to 85% of the subject's MAWL for that frequency. One trial consisted of ten lifts of a combination of speed, frequency and %MAWL with the last two lifts collected for data analysis. The number of lifts performed for each trial was selected as ten to allow the subject to get the rhythm of the specified lifting frequency. The actual lifting time for any one trial was an average of 5 minutes, with a 10 minute rest break per trial. The average expected total duration of a trial was 15 minutes. Accounting for all variable combinations,

Subject	Lifting Speed																	
	Normal									Fast								
	Lifting Frequency (lifts/min)									Lifting Frequency (lifts/min)								
	1			4			8			1			4			8		
	%MAWL			%MAWL			%MAWL			%MAWL			%MAWL			%MAWL		
	35	60	85	35	60	85	35	60	85	35	60	85	35	60	85	35	60	85
1	x x																	
2																		
3																		
4																		
5																		

Figure 1. Design for Experiment 1.

each subject performed 36 trials for Experiment 1. All normal speed trials were performed before the fast speed trials so as not to bias the normal speed trials.

The levels of each of the three independent variables are summarized below:

(0) Block: Subjects (5 subjects)

(1) Whole Plot: Lifting speeds (2 levels)
normal and fast

(2) Split Plot: Lifting frequency (3 levels)
1, 4 and 8 lifts per minute

(3) Split-Split Plot: % MAWL (3 levels)
35, 60, and 85 %

The response variables were:

(1) Magnitude of peak vertical force applied in the vertical (y) direction by hands

(2) Magnitude of peak horizontal force applied in the horizontal (x) direction by hands

(3) Maximum compression force at L5/S1 during the pull phase

(4) Maximum shear force at L5/S1 during the pull phase

(5) Time to complete lift

The mathematical model for this experimental design is:

$Y_{ijklm} = m + B_i + S_j + F_k + SF_{jk} + L_l + SL_{jl} + FL_{kl} + SFL_{jkl} + \text{Error A} + \text{Error B} + \text{Error C} + d_{ijklm}$

Where: Y_{ijk} = Measured observation (see defined response variables above)

m = Common effect in all observations

B_k = Effect due to blocking on subjects

S_j = Effect due to speed

F_k = Effect due to frequency

SF_{jk} = Combined effects of speed and frequency

L_l = Effect due to load (%MAWL)

SL_{jl} = Combined effects of speed and load (%MAWL)

FL_{kl} = Combined effects of frequency and load (%MAWL)

SFL_{jkl} = Combined effects of speed, frequency and load (%MAWL)

Error A = error of whole plot (Combined effects of subject and speed)

Error B = error of split plot (Combined effects of subject and speed, subject and frequency, and subject and frequency and speed)

Error C = error of split-split plot (Combined effects of subject and load, subject and load and speed, subject and load and frequency, and subject and load and frequency and speed)

d_{ijklm} = sampling error term.

The ANOVA table for N = 5 and degrees of freedom (df) corresponding to effects is shown in Table 1.

Experiment 2: Speed and Weight Effects

Experiment 2 tested the effects of absolute weight increments and lifting speed on the peak hand forces at a lifting frequency of 1 lifts per minute. The independent variables for this experiment were weight and lifting speed. The number of levels for the absolute weight variable were 5 increments ranging from 6.25 kg to 24.77 kg. To balance the experimental design the heaviest weight increment was the minimum 85%MAWL of the 5 subjects. The levels of lifting speed were normal and fast. The experimental design was a split plot factorial blocked on subjects with two samples per cell; this design is illustrated in Figure 2. The whole-plot variable was lifting speed. The split-plot variable was weight.

Table 1. ANOVA Table for Experiment 1.

Source	degrees of freedom
B_k	4
S_j	1
F_k	2
SF_{jk}	2
L_l	2
SL_{jl}	2
FL_{kl}	4
SFL_{jkl}	4
Error A	4
Error B	16
Error C	48
Sample Error	90
Corrected total	179

Subject	Lifting Speed at 1 lift per minute									
	Normal					Fast				
	Weight of Load (kg)					Weight of Load (kg)				
	6.25	10.91	15.45	20.00	24.77	6.25	10.91	15.45	20.00	24.77
1	x x									
2										
3										
4										
5										

Figure 2. Design for Experiment 2.

The subjects lifted the container which contained a load ranging 6.25 kg to 24.77 kg in weight. One trial consisted of ten lifts of a combination of speed and weight, with the last two lifts collected for data analysis. The number of lifts to be performed for each trial was selected as ten to allow the subject to get the rhythm of the specified lifting frequency. The actual lifting time for any one trial was a maximum of 5 minutes, with a 10 minute rest break per trial. The total expected duration of a trial was 15 minutes. Accounting for all variable combinations, each subject performed 24 trials for Experiment 2.

The levels of each of the independent variables are summarized below:

(1) Block: Subjects (5 subjects)

(2) Whole Plot: Lifting speed (2 levels)
normal and fast

(3) Split Plot: Weight lifted (5 levels)
6.25, 10.91, 15.47, 20.00 and 24.77 kg

The response variables were:

(1) Magnitude of peak vertical force applied in the vertical (y) direction by hands

(2) Magnitude of peak force applied in the horizontal (x) direction by hands

(3) Maximum compression force at L5/S1 during the pull phase

(4) Maximum shear force at L5/S1 during the pull phase

(5) Time to complete lift

The mathematical model for this experimental design is:

$$Y_{ijk} = m + B_i + S_j + W_l + SW_{jl} + \text{Error A} + \text{Error B} + d_{ijkl}$$

Where: Y_{ijk} = Measured observation (see defined response variables above)

m = Common effect in all observations

B_k = Effect due to blocking on subjects

S_j = Effect due to speed

W_l = Effect due to weight

SW_{jl} = Combined effects of speed and weight

Error A = error of whole plot (Combined effects of subjects and speed)

Error B = error of split plot (Combined effects of subjects and weight, and subjects and weight and speed)

d_{ijkl} = sample error term.

The ANOVA table for N = 5 and degrees of freedom (df) corresponding to effects is shown in Table 2.

The Y_{ijk} terms, or response variables, are the maximum (peak) magnitudes of the vertical and transverse forces applied to the handle of the container during the data collection period.

Statistical analysis of the two experiments was then repeated, adding an Analysis factor to each experiment. The Analysis factor had two levels, called Conditions 1 and 2, defined as follows. Condition 1 was the situation where the forces applied to the load and the forces at L5/S1 were calculated by the model. Condition 2 was the situation where the applied forces were measured and then input into the model for the calculations of the forces at L5/S1. Since the Analysis factor was a significant main effect on all response variables, the mean values of the forces were compared under Conditions 1 and 2 with a paired t-test for all variables.

Phase IV

In this phase the biomechanical model was utilized to calculate peak externally applied loads at the hands and then these calculated forces were compared to measured hand forces as indicated by the strain-gage apparatus. The resulting forces at L5/S1 as derived from the model with the measured and calculated applied forces were also compared.

Table 2. ANOVA Table for Experiment 2.

Source	degrees of freedom
B_k	4
S_j	1
W_l	4
SW_{jl}	4
Error A	4
Error B	32
d_{ijkl}	50
Corrected total	99

The Biomechanical Model

The Dynalift biomechanical model treats the body as a series of rigid links and was developed for analysis of two-hand symmetric lifting by Ayoub et al. (1986). The Dynalift package analyzed body-segment kinematics and kinetics, and internal forces on the lumbosacral discs generated by sagittal-plane lifting or lowering tasks. A six-segment model is utilized to represent the human performing the lifting or lowering activity (see Figure 3), and task variables such as weight of load, box size, lifting distance, lifting technique, etc., were defined to best describe the lifting task. The joint location data was an ASCII file of raw data (x, y coordinates of the joints) obtained from frame-by-frame digitizing of video film of the lifting task.

To calculate forces acting at L5/S1, a series of cumulative equations were used, beginning with the reaction forces at the hand. The reaction forces at the hand represent the applied forces by the hand to the load during the lift. The reaction forces were then calculated at each of the successive joints: wrist, elbow, shoulder and L5/S1; each successive calculation depended on the reaction forces calculated at the preceding joint. The hand is the only segment which directly contacts the load and measurement of the forces applied through this contact and the resulting L5/S1 forces are the purposes of this study. It follows that increases/decreases/changes in the measured versus predicted (by the biomechanical model) hand forces may also be reflected in the calculations of the compression forces at L5/S1.

The Dynalift program uses the following inputs into the model: joint location data (two-dimensional X and Y coordinates of the joints in time series), anthropometric data (body measurements of the subject), and weight of the load. Specifically, the input consisted of the following information:

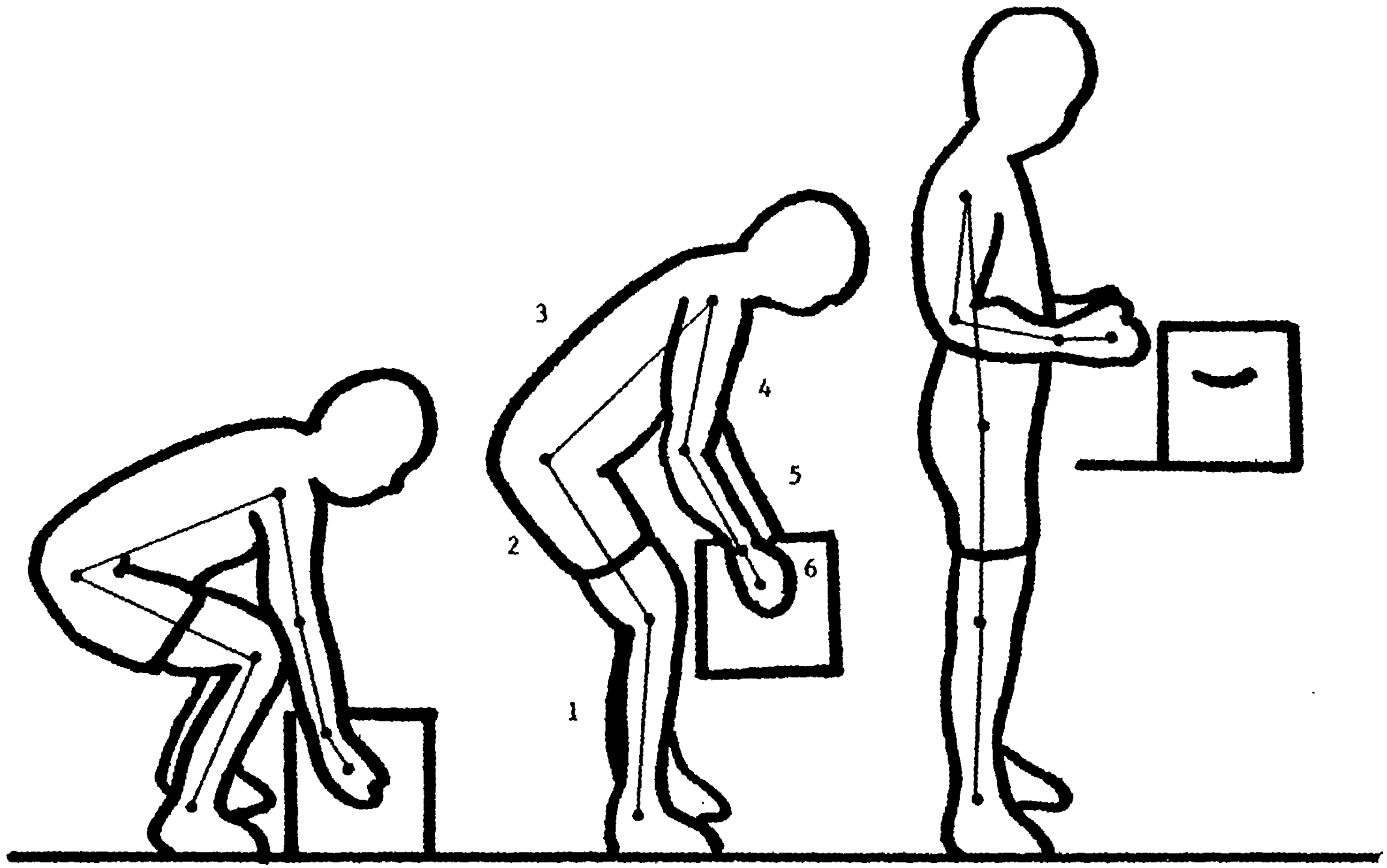


Figure 3. Representation of the human body using six segments:
1. lower leg
2. upper leg
3. trunk
4. upper arm
5. lower arm

(1) subject: weight (kg), height (m) and abdominal depth (m)

(2) link lengths (m): lower leg, upper leg, trunk, upper arm, lower arm and hand

(3) task characteristics: weight (kg), height of container (m), width of container (m), starting height (m) and ending height (m)

(4) total number of frames

(5) time increment of frame

(6) initial posture of the subject (angle of ankle, knee and hip).

The biomechanical model then utilized this input to determine the motion trajectory of each body segment and the compression forces acting on the lumbar spine. The model produces several intermediate calculations including: angular velocity of the body segments, angular acceleration of the body segments, linear acceleration of the center of mass of the segments, reaction and inertial forces at the joints and center of mass of the segments. These intermediate calculations were then used to calculate the compression and shear forces, as well as the moment, at the lower back (namely the L5/S1 joint). The hand joint and corresponding forces and torques as modeled in the Dynalift program are shown in Figure 4. For this research, the model was executed under two conditions:

(1) Reaction forces at the hands were calculated using kinetic equations. For this case, the reaction forces at the hand were calculated by the equation F=ma. The X reaction force at the hand was determined as the combined mass of the hands and load multiplied by the acceleration in the X direction. The Y reaction force at the hand was determined as the combined mass of the hands and load multiplied by the acceleration in the Y direction added to the weight of the load.

(2) Condition in which the measured reaction forces at the hands were used in the model. For this case, the X and Y reaction forces at the hands were not calculated as in Condition 1, but directly measured from the strain gages attached to the handle of the container.

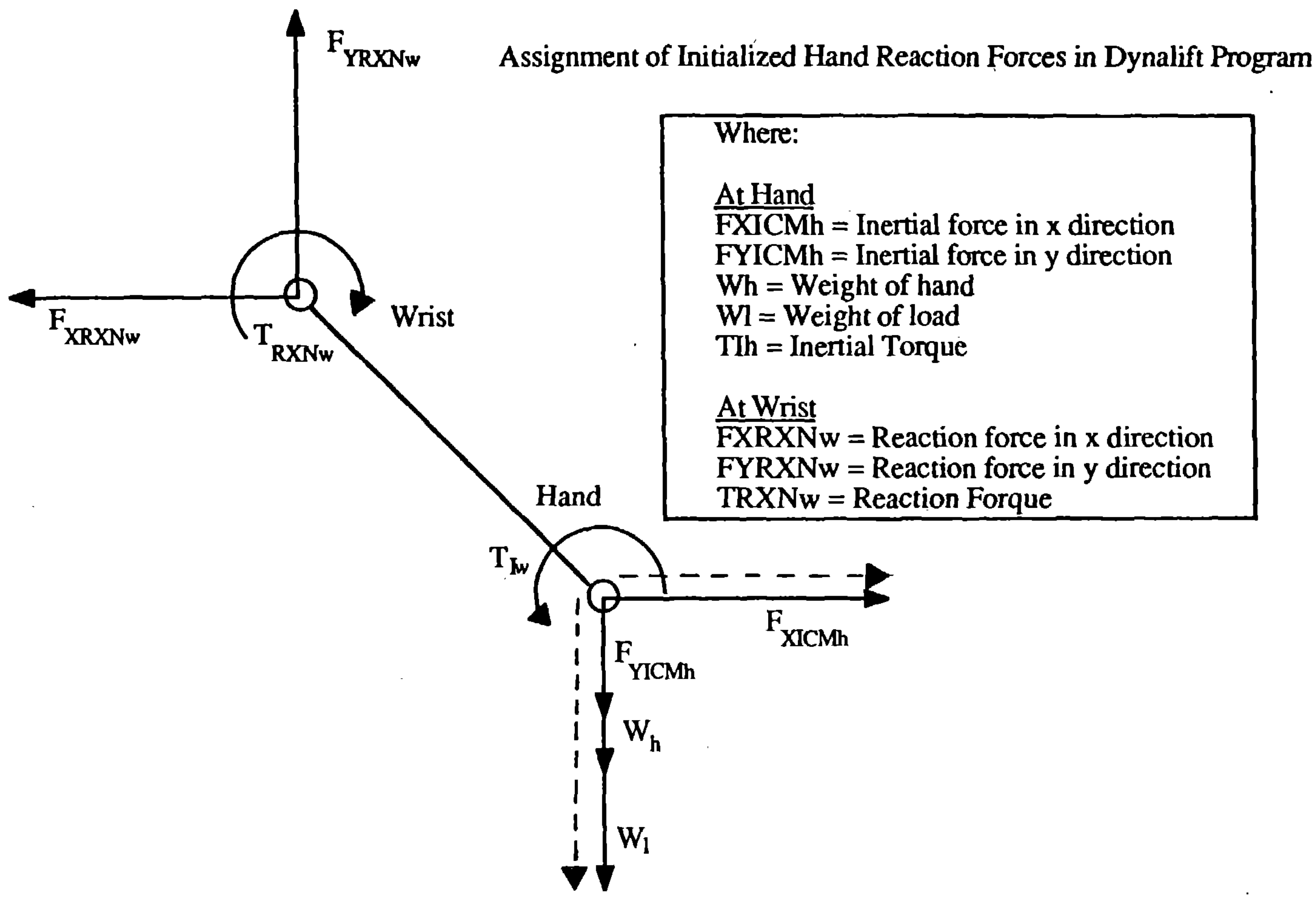


Figure 4. Hand segment forces and torques as calculated by the Dynalift program.

As shown in Figure 4 the calculated forces and total reaction forces at the wrist (shown as dashed arrows in Figure 4) were replaced by measured forces from the apparatus. Refer to Figure 5 for a summary of the approach used to compare the results of the biomechanical model and measured reaction forces in this study. The model was then initialized with the measured applied forces of the hands.

Necessary changes to the programming code of the model were minor and are described below:

(1) Changes to the data input routine accounted for new format of data collected from a new filming system which provided the necessary model input, but in different format than input data for the original Dynalift.

(2) Addition of the subroutine which read in direct A/D data and calculated the forces and substituted these forces for reaction forces at the hand in Dynalift.

(3) Changes to the data output routine to include kinematic and kinetic calculations for the body segments and joints under conditions 1 and 2.

The model employed a digital filter with a cutoff frequency of 2.0 to smooth raw joint displacement data. A cutoff frequency of 8.0 was examined to determine if the expected peaks hand acceleration would be evident at this frequency. At this higher frequency the peak in hand acceleration was still not evident and the quality of analysis was decreased due to excessive noise. The hand forces calculated with the model and digital filter cutoff of 2.0 were compared to the measured hand forces. An interesting observation was that the only difference between the modeled and calculated curves was the peak in the pull phase and toward the end of the lift. This was a reasonable result since the peak in hand forces was expected to occur before the liftoff in which case the peak in force corresponding to a peak in acceleration would not be evident in the modeled results. Analysis of the data with a cutoff frequency of 2.0 elicited results strikingly similar to the measured data, therefore strongly supporting the use of this cutoff frequency.

	Condition 1 (vs)	Condition 2
Model Inputs	Joint Location Data in Time Series Anthropometric Data Weight of Load	Joint Location Data in Time Series Anthropometric Data Weight of Load
Biomechanical Model	Dynalift	Dynalift
Intermediate Calculations	Angular Velocity Angular Acceleration Linear Acceleration XY Forces at Joints XY Forces at Hands	Angular Velocity Angular Acceleration Linear Acceleration XY Forces at Joints Use Measured XY Forces at Hands
Final Results	L5/S1 Compression (Normal Force) L5/S1 Shear (Parallel Force)	L5/S1 Compression (Normal Force) L5/S1 Shear (Parallel Force)

Figure 5. Illustration of approach using the Dynalift model under 2 conditions: Calculated forces at the hands and measured forces at the hands.

Apparatus

The experiment involved collecting data from three laboratory apparatus: video camera and digitizing system, strain gages attached to the handles of the container, and sensors which detected if the load had been lifted from the ground. All data were synchronized.

Design of Container and Handles

The container shown in Figure 6 was designed so that the weight of the load within the container was transferred to the handles so that resulting strain was detected. The design of the internal container frame and method of incrementing weight are illustrated in Figure 7. Incremental weight was added to the frame as shown in Figure 7. The overall dimensions of the container were 45.72 (frontal plane) x 30.48 (transverse plane) x 30.48 (sagittal plane) cm. The weight of the empty container was 5.68 kg.

The handle was designed for the application of the strain gages. The design of the handles and the frame attachments are shown in Figures 8 and 9. Dimensions of the handle "struts" were selected as the minimum dimensions allowing side-by-side placement of the strain gages.

Strain Gage Setup

Strain gages were mounted on the "strut" of the left handle as shown in Figure 10. Eight strain gages (two sets of four) were mounted on the handle, as shown in Figure 11. Channel 1 measured strain due to force on the handle in the vertical (y) direction. Channel 2 measured strain due to force on the handle in the horizontal (x) direction. Four strain gages constituted a channel, as shown in Figure 12. Each of these channels was configured as a four-arm wheatstone bridge as shown in Figure 12. The type of strain gage was selected based on specific application, and descriptions of the strain gages used for this study are listed in Table 3.

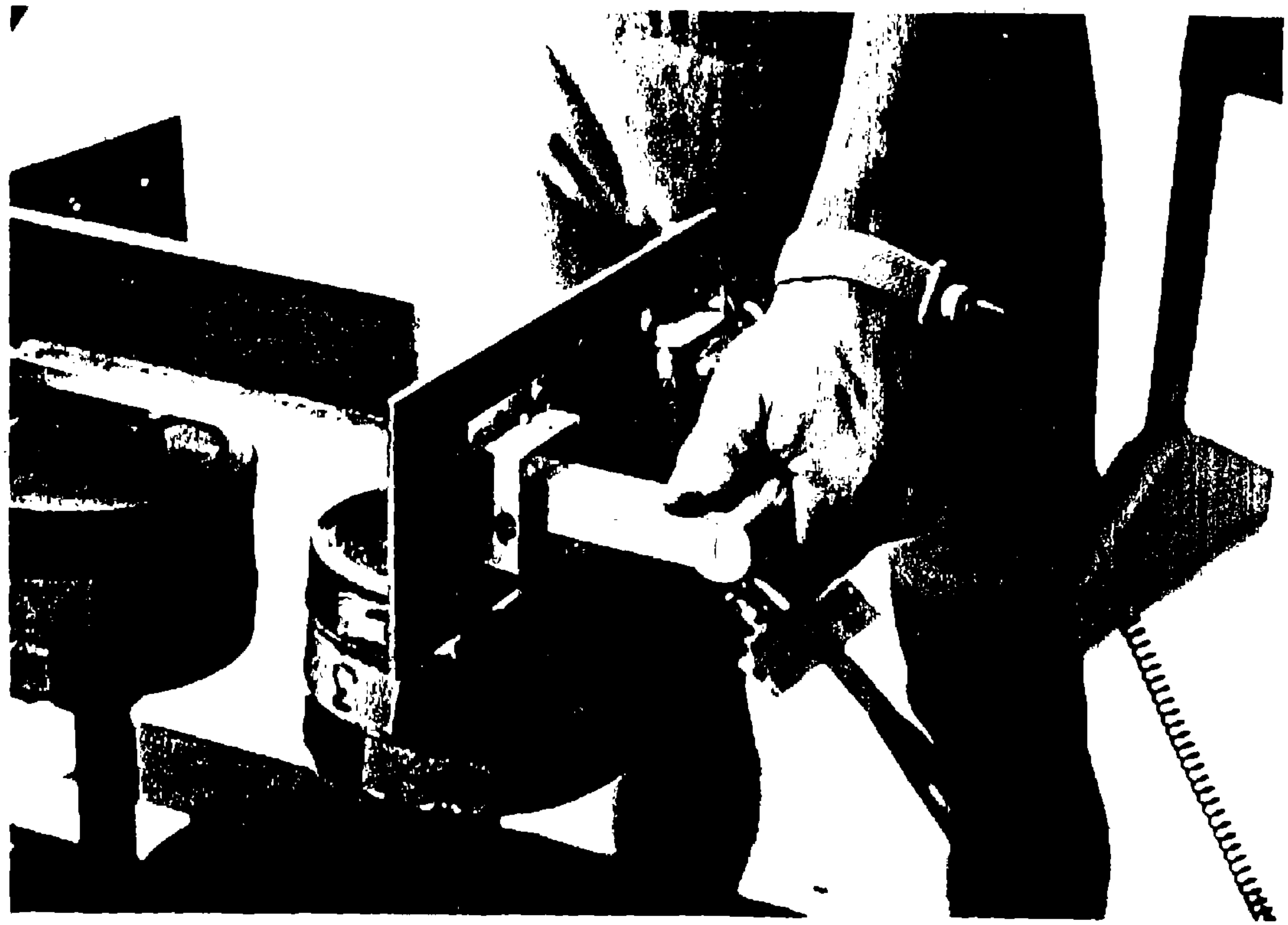
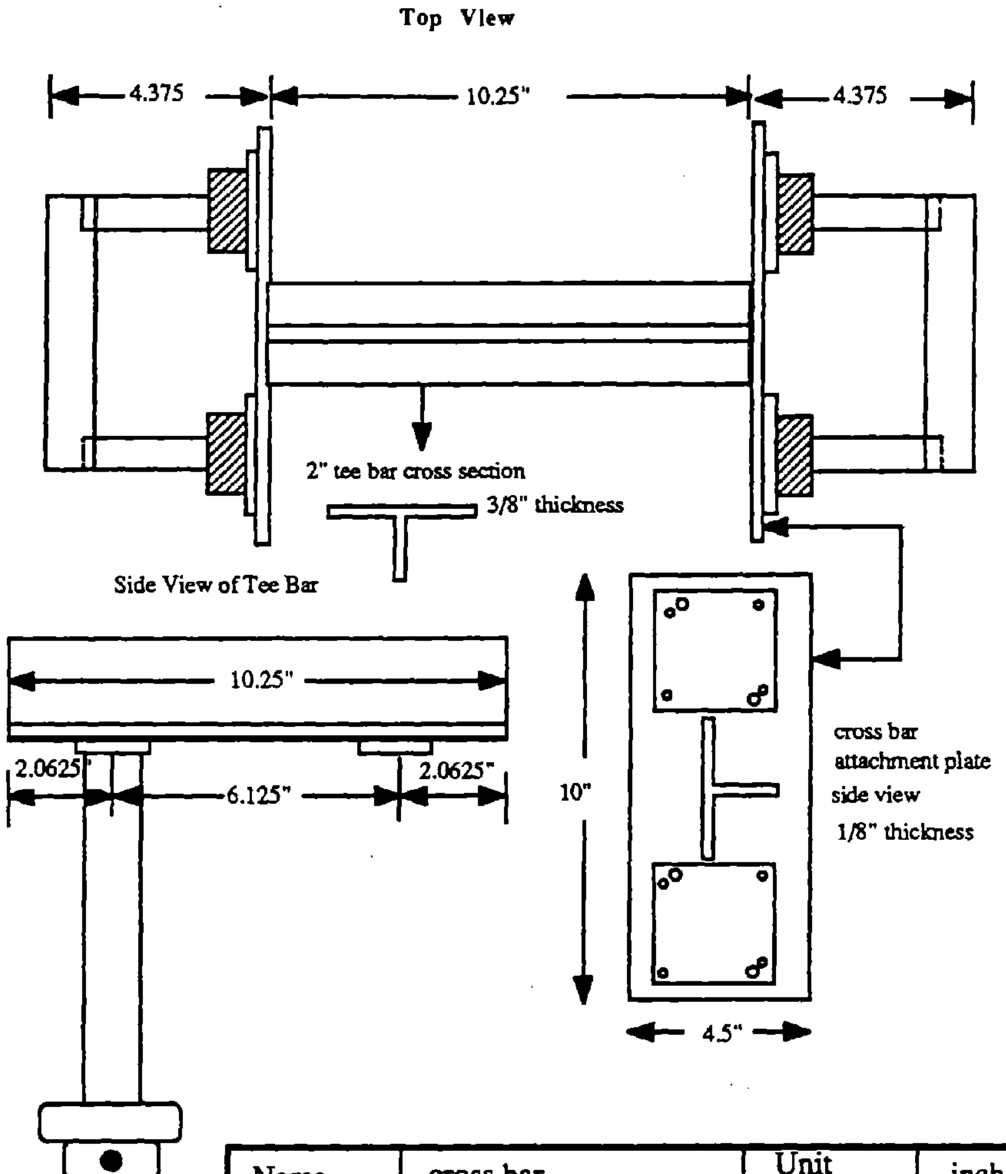
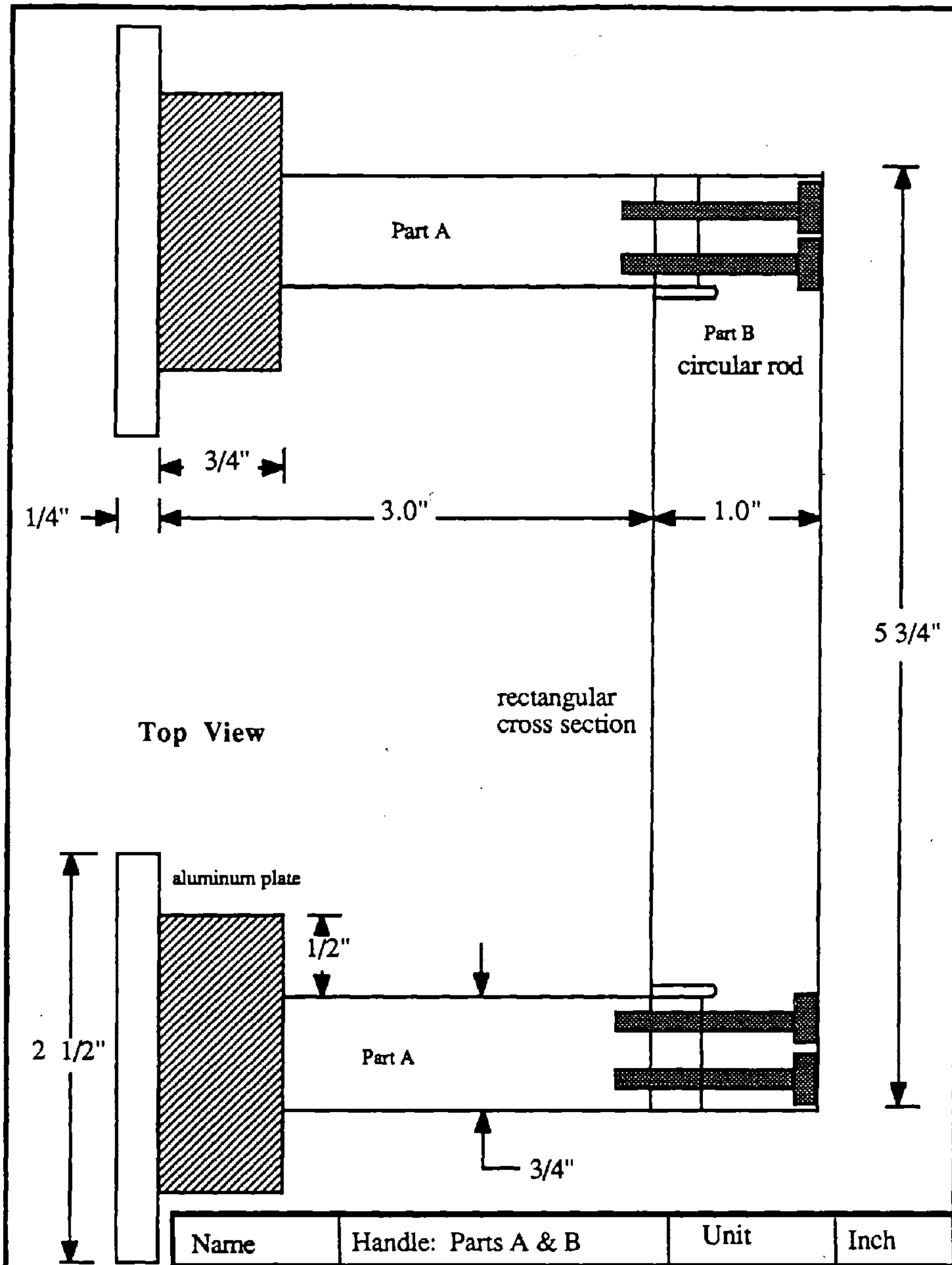


Figure 6. Front photographic view of the apparatus.



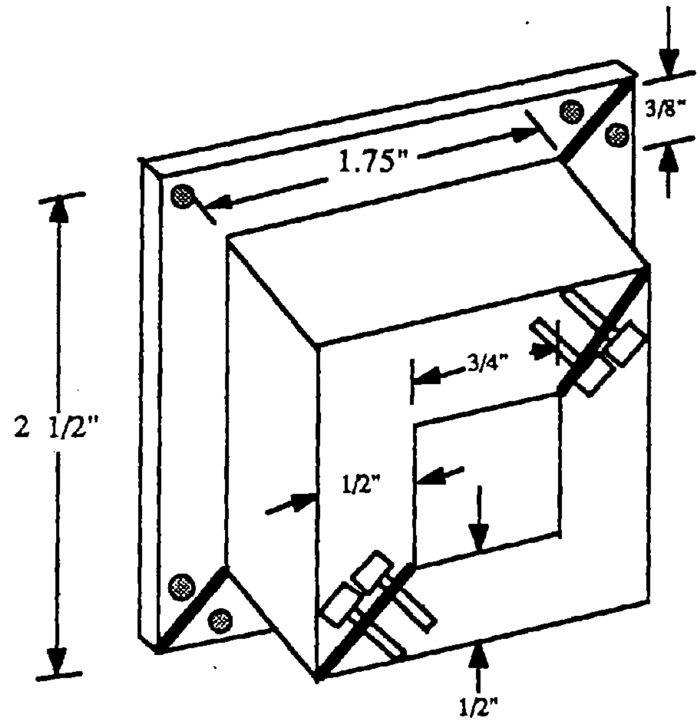
Name	cross bar	Unit	inch
Type	t section	Scale	3"=1"
Material	aluminum 6061	Amount	2
Name	cross bar attchmt plate	Unit	inch
Type		Scale	
Material	steel	Amount	4

Figure 7. Top view of box frame with weight-holding scheme.



Name	Handle: Parts A & B	Unit	Inch
Name	A: bar B: grip	Scale	1"=1"
Material	aluminum 6061	Amount	A: 8 B: 4

Figure 8. Drawing of handle.



Name	Attachment Plate	Unit	inch
Type		Scale	1"=1"
Material	aluminum 6061	Amount	8

Figure 9. Attachment plate for handle to end of frame.

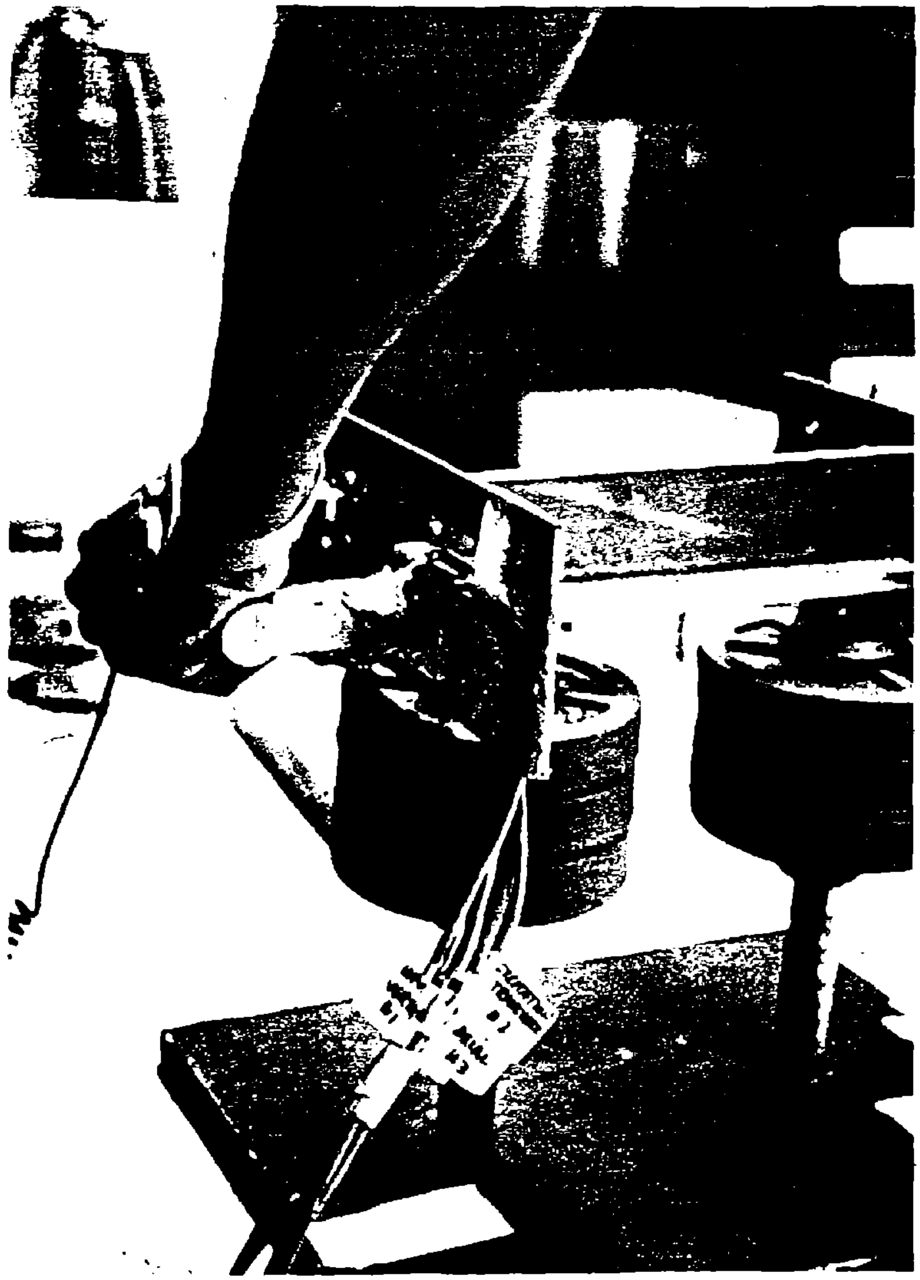


Figure 10. Photographic view of the strain gage instrumented handle.

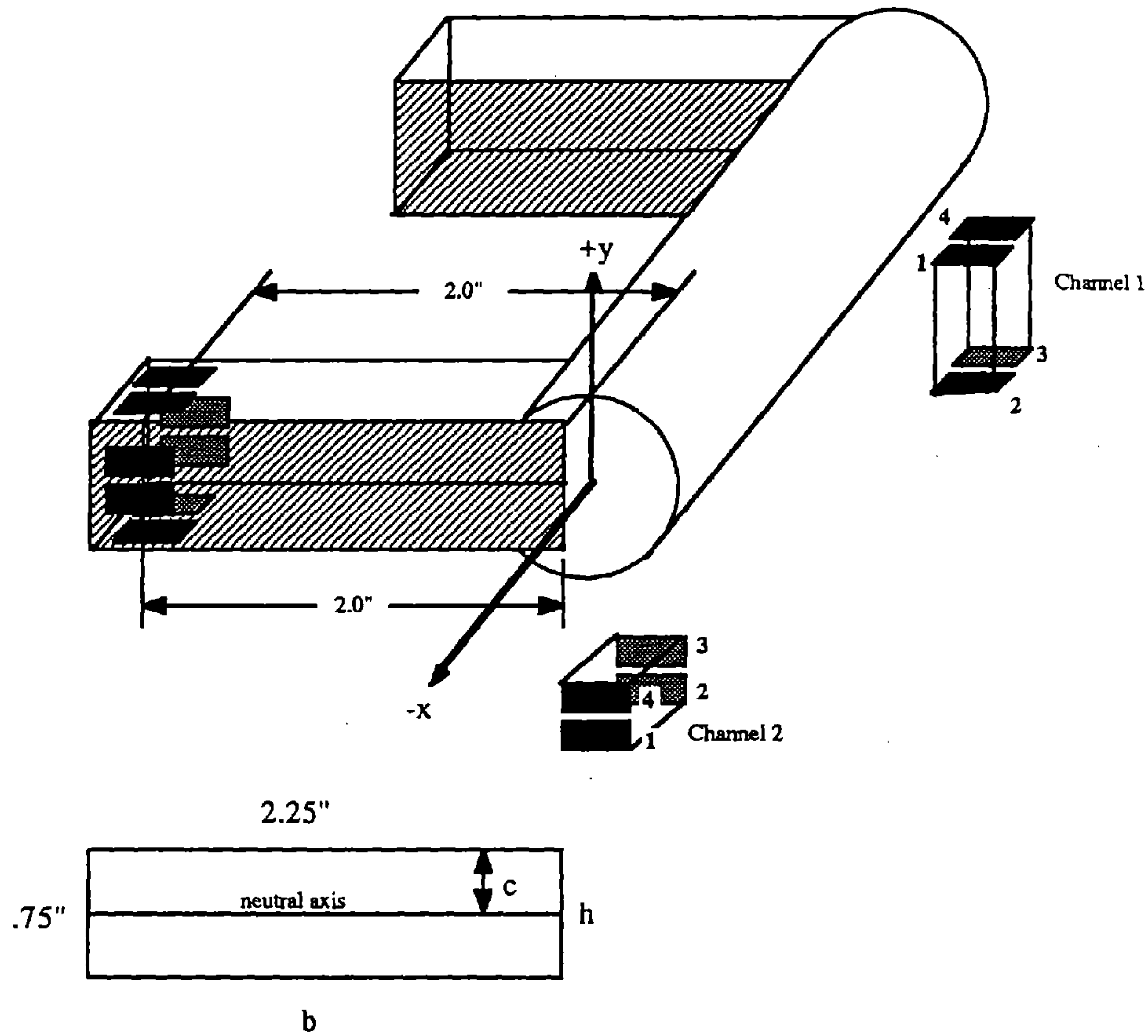


Figure 11. Location of strain gages on handle (not to scale), and orientation of the gages for each of the two channels.

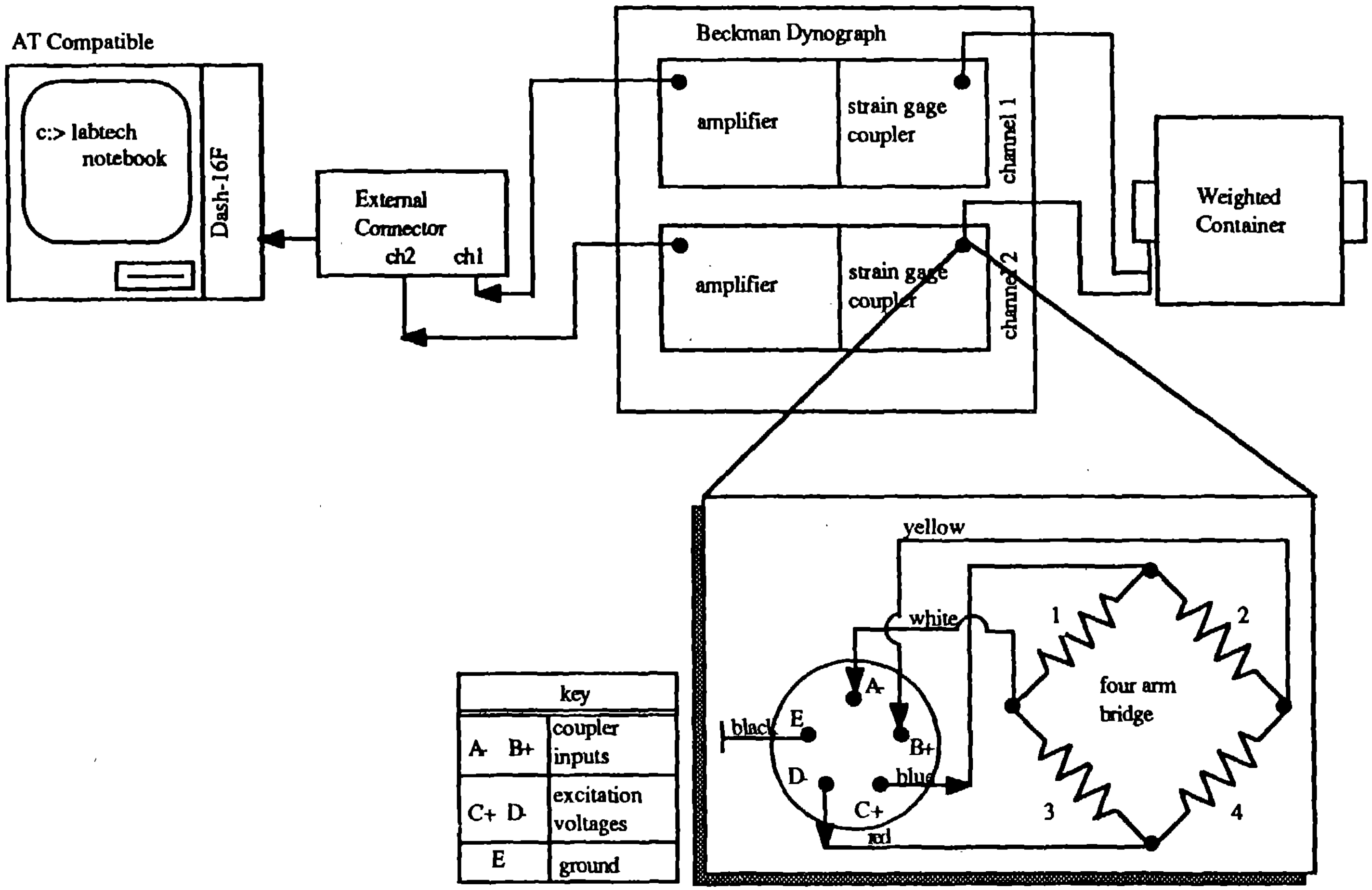


Figure 12. Schematic diagram of the data acquisition setup.

Table 3. Strain Gage Specifications

Manufacturer	Micro-Measurements (MM)
Part No.	CEA-13-250UN-350
Gage Factor at 75°F	2.12 ±.5%
k_t	±.5%
tab area	.08 x .05 in 2.0 x 1.1 mm
thermal expansion coefficient (ppm/°F)	11.1 - 12.9 (32-212 °F)

Analog output from the strain gage is a voltage differential comparing the strained versus unstrained states of the handle, caused by the change in resistance of the gage corresponding to degree of strain on the handle. Depending on the type of strain gage bridge circuit, the strain is calculated using the output voltage, known resistances and the gage factor. Calculations for strain and forces for a four-arm wheatstone bridge setup are given below. Corresponding variables are labelled with reference to handle dimensions in Figure 11.

Strain (e) = $-V_r$ / GF (1)

where: $-V_r$ = difference in voltage between the strained and unstrained states

GF = gage factor (given by manufacturer) = 2.12.

Vertical (Channel 1) and transverse (Channel 2) forces are calculated from known strain using the following formulae:

$F = E\,e\,I / d\,c$ (2)

where: E = modulus of elasticity for Reynolds aluminum 6061 (7.12×10^5 kg/cm^2) given by manufacturer

e = strain derived as above

$I = bh^3 / 12 = (1.905)^4 / 12 = 1.097$ cm^4

d = distance from center of handle diameter to center of strain gage = 5.08 cm

c = distance to neutral axis = 1.905/2 = .9525 cm.

An A/D converter was used to transform the analog gage output voltage into digital data. The strain gage channels consisted of one input (excitation) voltage cable and one output voltage cable. Each of the cables consisted of two conductors with a shield, and had a phono plug attached to it. An octal phono jack was mounted to the box frame which received a phono plug for each channel.

Signal Amplification

The Beckman R-511A recorder and strain gage coupler #9803 was used to provide excitation voltage to and amplify voltage output from the strain gages. One strain gage coupler was used for each channel of gages, and each coupler was associated with its own preamplifier and amplifier controls. The strain gage coupler was altered for a four-arm bridge configuration as directed by the Beckman manual. The coupler was equipped with a balance control which balanced the strain gage channel at zero voltage. Each strain gage channel corresponded to a mechanical pen on the recorder which recorded the output voltage of the channel in terms of millimeters of deflection of the pen. Each coupler was equipped with an output jack which enabled the millimeters of deflection to be reported as output voltage to the A/D converter. Calibration was performed by loading the apparatus with exact known weight and adjusting the sensitivity and gain settings of the amplifier to elicit voltage which would yield the calculated weight load within $\pm$ 2% of the known load. Settings were consistent for light and heavy loads so calibration was performed before and after each subject's test session.

Weight Sensors

Four electric momentary push button switches were used to determine the exact moment in time when the load had completely left the ground. One switch was located under each of the four corners of the load while it was sitting on a platform. The weight of the load pressed the switch in the "off" position, registering approximately zero voltage. When the load was lifted up, the switch was released and the voltage increased to approximately 2.4 V. Each of the four switches was independently wired, and one of the circuits served as TTL input into the video processor to synchronize all data. The switches were imbedded in a plywood platform measuring 3 x 6'. Each switch circuit was powered by an independent power supply.

Metrabyte Dash 16 A/D Converter

The process of data acquisition was controlled by the Labtech Notebook software package. A/D conversions of voltages ± 5 volts were made with the Metrabtye Dash 16 directly to a data array, at a sample rate of 60 Hz per channel. The A/D converter accepted up to eight channels in the differential channel mode. The strain gages, amplifier, and A/D converter setup is shown in Figure 12. The Dash 16 converted two strain gage channels and voltage from four sensors which were activated if the box had left the ground, for a total of six channels.

Synchronization of Data

All video displacement data and A/D data were synchronized. Both video cameras and the A/D converter sampled data at 60 Hz. The data were matched by sample using the momentary switch system described above. Voltage output from one of the switches was monitored by the video processor. When the voltage output registered as a TTL event (a change in voltage from less than .4 V to greater than 2.4 V), the corresponding video frame was automatically labelled with this event. All data were time-matched with this information.

Camera Data

A computer-based human motion analysis system, ExpertVision, was used to record the trajectories of the joints during the lifting motion in terms of three-dimensional cartesian coordinates of the joint centers and the container c.m. Three video cameras (60 fps), controlled by a video processor, captured the coordinate data during execution of a lift. These data were then written to files on the Sun computer.

The joint centers of the subject were identified by reflective markers. During the filming process, these markers, or targets, were converted by software procedures to centroids by averaging the coordinates of the individual pixels forming the outline of the marker. The centroids of each joint were then linked from frame to frame to form trajectories of the movement of the individual joints. This information was then saved in ASCII files which served as input data for the biomechanical model.

CHAPTER IV

RESULTS

The general objective of the study was to measure the forces applied by the hands to the load and calculate resulting L5/S1 forces during floor-to-knuckle height lifting at normal and fast speeds with various loads. It was hypothesized that direct measurement of hand forces would exhibit peak forces applied during the pull phase of the lift, showing that lifting is not a smooth motion. In addition, it was expected that the peak hand forces would occur immediately before the liftoff, sooner than the biomechanical model calculations indicate. It was also hypothesized that these measured peak applied forces and the resulting modeled peak L5/S1 forces would be greater in magnitude than originally calculated using the biomechanical model without the measured hand forces.

The effects of speed of lift, frequency of lift, %MAWL and weight of the load on the measured peak forces applied by the hands to the load and resulting forces at L5/S1 were investigated with two experiments. Experimentation to examine these variables was executed in four phases: (1) subject measurement and familiarization, (2) determination of MAWL, (3) collection of video and A/D data under the experimental conditions and (4) analysis of data with biomechanical model and statistics. Experiment 1 investigated the effects of speed of lift, frequency of lift and %MAWL on the following response variables during the pull phase of the lift: peak horizontal and vertical forces applied by the hands to the load, peak compression and shear forces at L5/S1 and time to complete the lift. Experiment 2 investigated the effects of speed of lift and weight of load at a frequency of 1 lift per minute (lpm) on the same response variables as listed above.

Subject descriptive data will first be presented, followed by comparison of the measured and calculated hand forces and resulting L5/S1 forces, and continuing with results of Experiments 1 and 2.

Subject Anthropometric Data

All subjects completed both experiments. Mean age of the subjects was 23.2 ± 2.77 years. Mean height and weight were 179.24 ± 1.73 cm and 89.86 ± 11.40 kg, respectively. Anthropometric data for each subject and group mean are presented in Table 4.

Subject MAWLs

MAWLs for the subjects were determined at each of the three lifting frequencies (1, 4 and 8 lpm) using the psychophysical approach by Snook (1978). The 15% criteria was met for each MAWL determination and no repeat trials were required.

MAWLs for each subject and group mean are shown in Table 5. There was no general trend in MAWLs between subjects. Mean MAWL at 1 lpm was 35.69 ± 8.88 kg, and ranged from 27.78 to 48.52 kg between subjects. Mean MAWL at 4 lpm was 27.52 ± 5.48 kg and ranged from 21.76 to 36.59 kg. Mean MAWL at 8 lpm was 17.80 ± 2.10 kg and ranged from 16.14 kg to 21.42 kg. MAWLs from this study are compared with those found by other investigators in Table 6.

Measured Versus Calculated Forces

Forces Applied by the Hands to the Load

The difference between the measured forces at the hand and those calculated by the biomechanical model were limited to the pull phase of the lift and the end of the lift (placement of the load at its destination). The measured and calculated forces at the hands

Table 4. Summary of anthropometric data of subjects.

Measurement	Subject ID 1	2	3	4	5	Mean ± s.d.
height (cm)	181.50	178.30	179.80	176.90	179.70	179.24 ± 1.73
weight (kg)	92.04	99.20	101.82	80.34	75.91	89.86 ±11.40
length (cm)						
l. leg lateral femoral condyle/lateral malleolus	42.50	41.70	43.50	42.00	41.45	42.23 ± 0.81
u. leg greater trochanter/lateral femoral condyle	41.00	39.60	40.50	38.50	40.80	40.08 ± 1.03
l. arm elbow axis/ulnar styloid	26.40	25.80	26.50	26.60	26.70	26.40 ± 0.35
hand wrist axis/knuckle II middle finger	10.05	10.10	9.50	9.10	9.60	9.67 ± 0.41
hip ht floor/greater trochanter	94.60	93.20	96.00	93.40	93.50	94.14 ± 1.17
shoulder ht floor/acromion process	148.20	146.20	146.10	145.85	145.70	146.41 ± 1.02
abdominal depth transverse plane: umbilicus/vertebrae	22.95	25.80	25.90	20.50	20.40	23.11 ± 2.70

Table 5. Subject MAWLs at 1, 4 and 8 lifts per minute.

Subject	1 lpm				4 lpm				8 lpm			
	%MAWL				%MAWL				%MAWL			
	100	85	60	35	100	85	60	35	100	85	60	35
1	34.77	29.55	20.86	12.17	25.79	21.92	15.47	9.03	17.21	14.63	10.33	6.02
2	40.00	34.00	24.00	14.00	36.59	31.10	21.95	12.81	17.56	14.93	10.54	6.15
3	27.78	23.61	16.67	9.72	26.25	22.31	15.75	9.19	16.65	14.15	9.99	5.83
4	27.04	22.98	16.22	9.46	21.76	18.50	13.06	7.62	21.42	18.21	12.85	7.50
5	48.52	41.24	29.11	16.98	27.22	23.14	16.33	9.53	16.14	13.72	9.68	5.65

Table 6. Summary of MAWLs (kg) at comparable frequencies by various investigators for floor-to-knuckle lift executed by male subjects.

Investigator No. and Type of Subjects	Frequency		
Present Study	1 lpm	4 lpm	8 lpm
5 college (18-30)	35.69 ± 8.88	27.52 ± 5.48	17.80 ± 2.10
Ayoub et al. (1978)	2 lpm	4 lpm	8 lpm
73 industrial	27.14 ± 8.36	25.81 ± 7.55	23.77 ± 7.73
Mital (1984)	1 lpm	4 lpm	8 lpm
37 industrial	16.83 ± 4.68	15.42 ± 4.52	14.99 ± 5.34
Snook (1978)	1 lpm	4.3 lpm	6.7 lpm
15 industrial	29.00 ± 6.70	25.00 ± 6.10	22.00 ± 5.50
Ayoub & Mital (1990)*	1 lpm	4 lpm	8 lpm
	20.56 ± 15.70	16.81 ± 12.88	15.10 ± 10.90

* Adjusted weighted means from Ayoub et al. (1978), Snook (1978) and Mital (1984)

of the carry portion of the lift showed little differences as determined by observation. The measured forces at the hands exhibited a distinctive deviation from the calculated force during the pull phase of the lift. When the lifting speed was fast, this deviation was usually a steep spike and exceeded the calculated curve. When the lifting speed was normal, the deviation varied, depending on the direction of the force. The vertical force at normal speed exhibited spikes in all trials with four exceptions: for one subject lifting at 1 and 4 lpm and 85 and 60 %MAWL, the spikes were small and did not exceed the calculated force. For these same lifting tasks the horizontal force at normal speed exhibited a deviation, but not in the form of a steep spike. For 1 and 4 lpm the horizontal force at the hands peaked, but then slowly returned toward the calculated curve. For 8 lpm, the lag time was not so slow, but the deviation could still not be considered a spike. Shown in Figures 13 through 21 are plots of the measured and calculated horizontal hand forces for two trials of each of the nine lifting tasks for a single subject performing at normal and fast speeds. Figures 22 through 30 are plots of the measured and calculated vertical hand forces for two trials of each of the nine lifting tasks for a single subject performing at normal and fast speeds. Deviations in measured from modeled forces during the placement of the load at its destination were due to positioning of the load by the subject. The fluctuation in hand forces applied to accomplish adjustment of the load while moving and targeting toward the destination are shown in the figures.

In general, the peak measured hand forces were statistically greater than the modeled forces for all conditions of lifting. However, when the measured forces were used as input into the biomechanical model, only the resulting calculated forces at L5/S1 for lifts executed at fast speed were significantly greater than those modeled without input of the measured forces. A detailed discussion of these results follows.

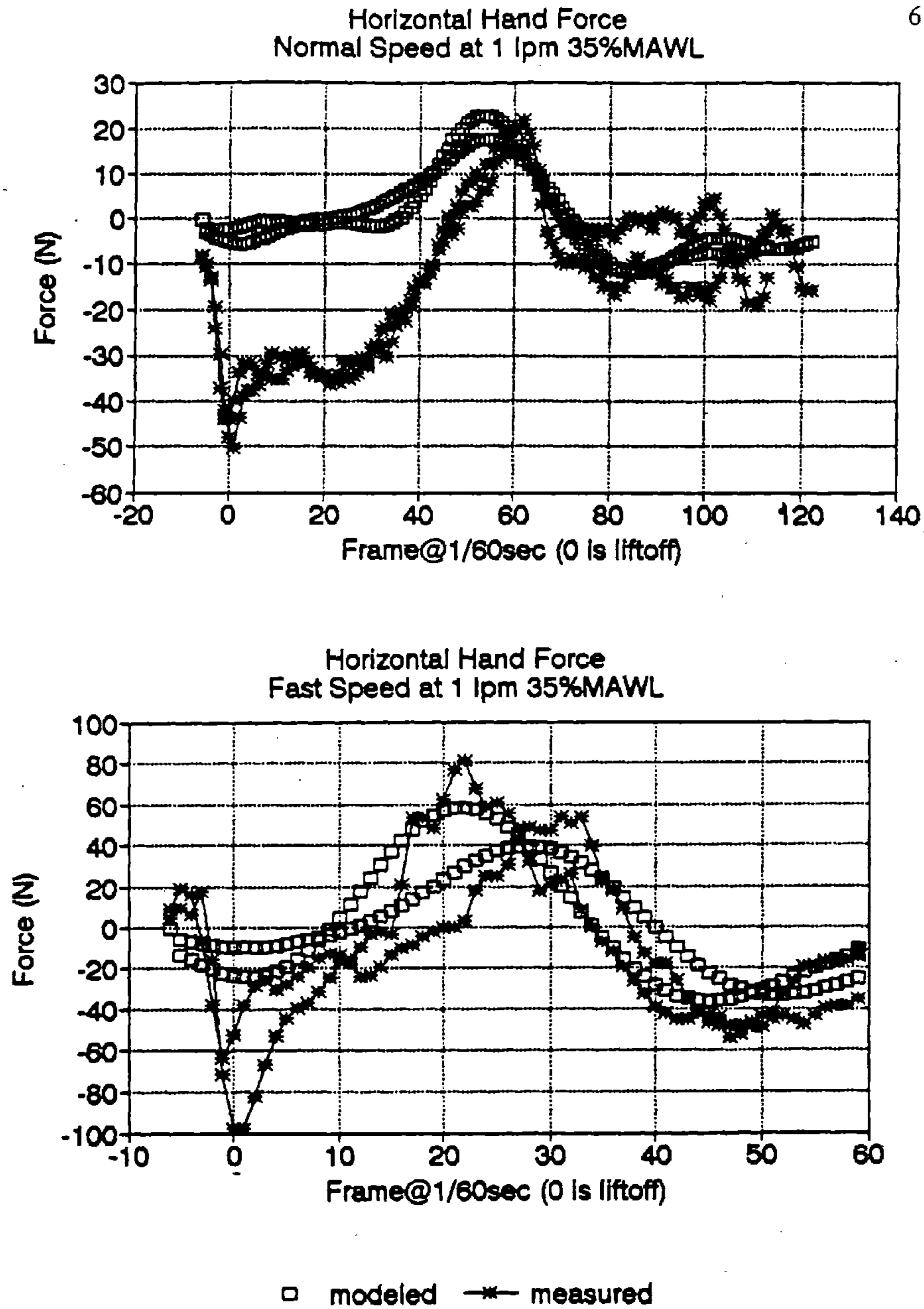


Figure 13. Plot of modeled and measured horizontal hand force for two trials at 1 lpm and 35% MAWL performed at normal (top) and fast (bottom) speeds.

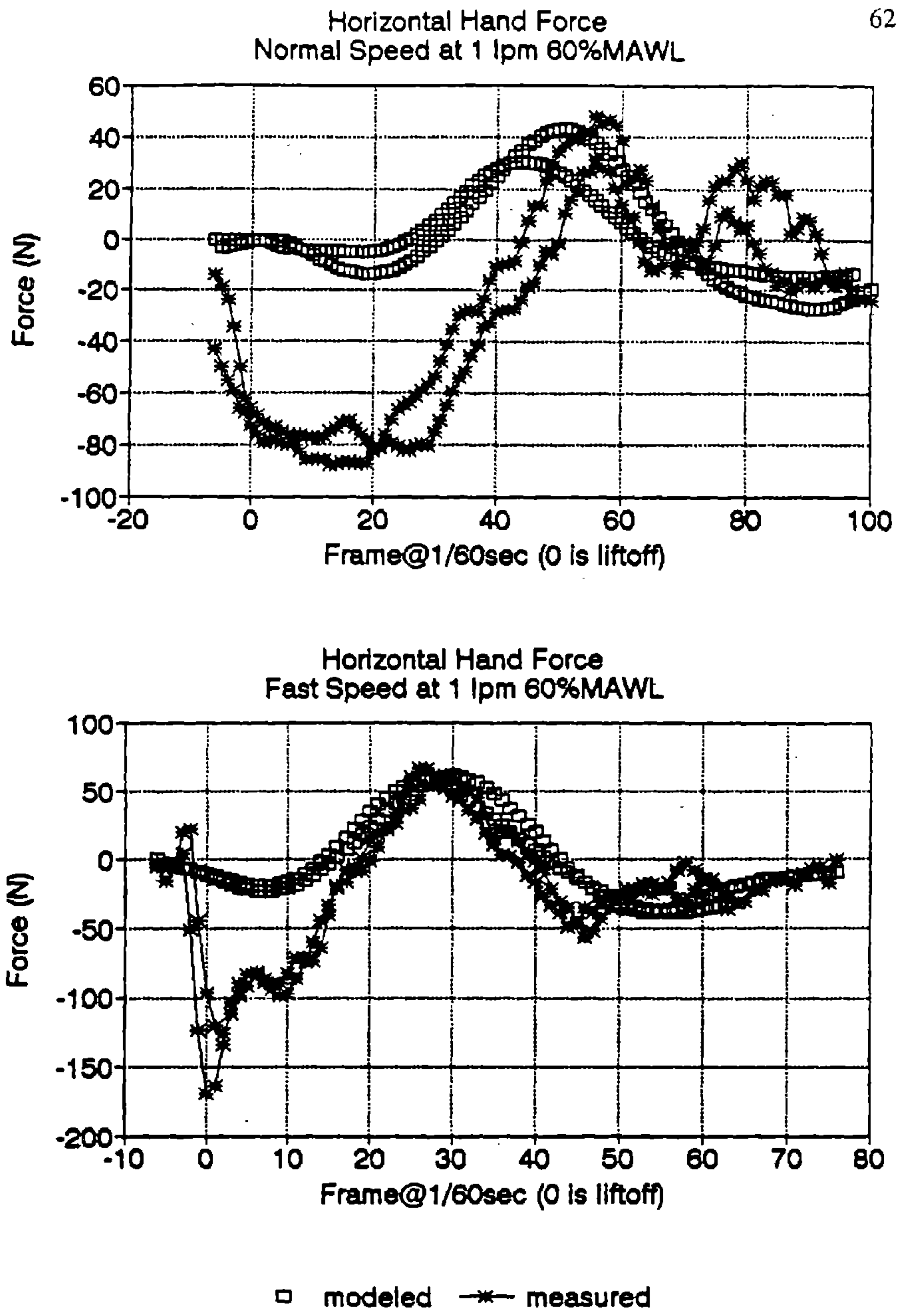


Figure 14. Plot of modeled and measured horizontal hand force for two trials at 1 lpm and 60% MAWL performed at normal (top) and fast (bottom) speeds.

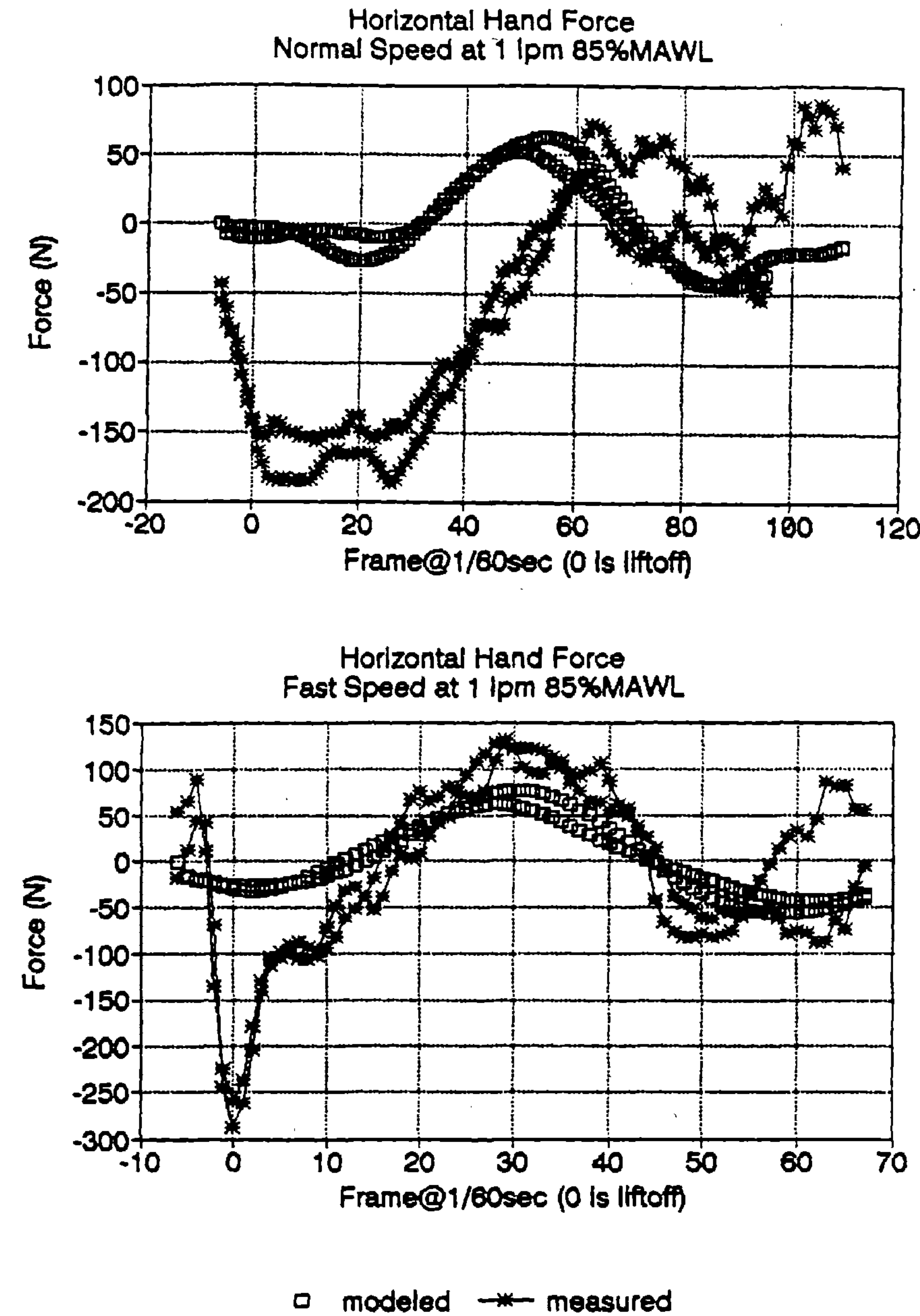


Figure 15. Plot of modeled and measured horizontal hand force for two trials at 1 lpm and 85% MAWL performed at normal (top) and fast (bottom) speeds.

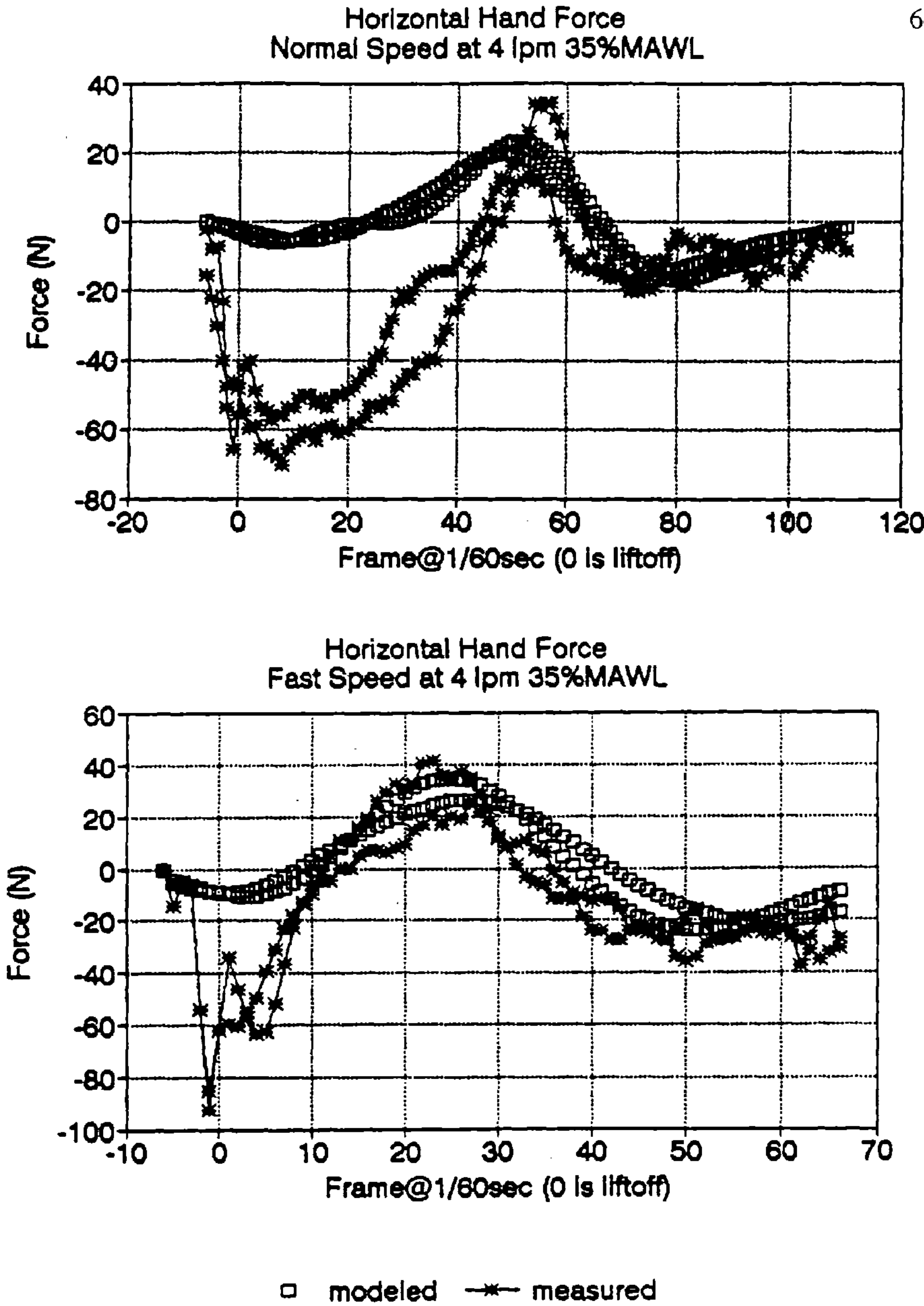


Figure 16. Plot of modeled and measured horizontal hand force for two trials at 4 lpm and 35% MAWL performed at normal (top) and fast (bottom) speeds.

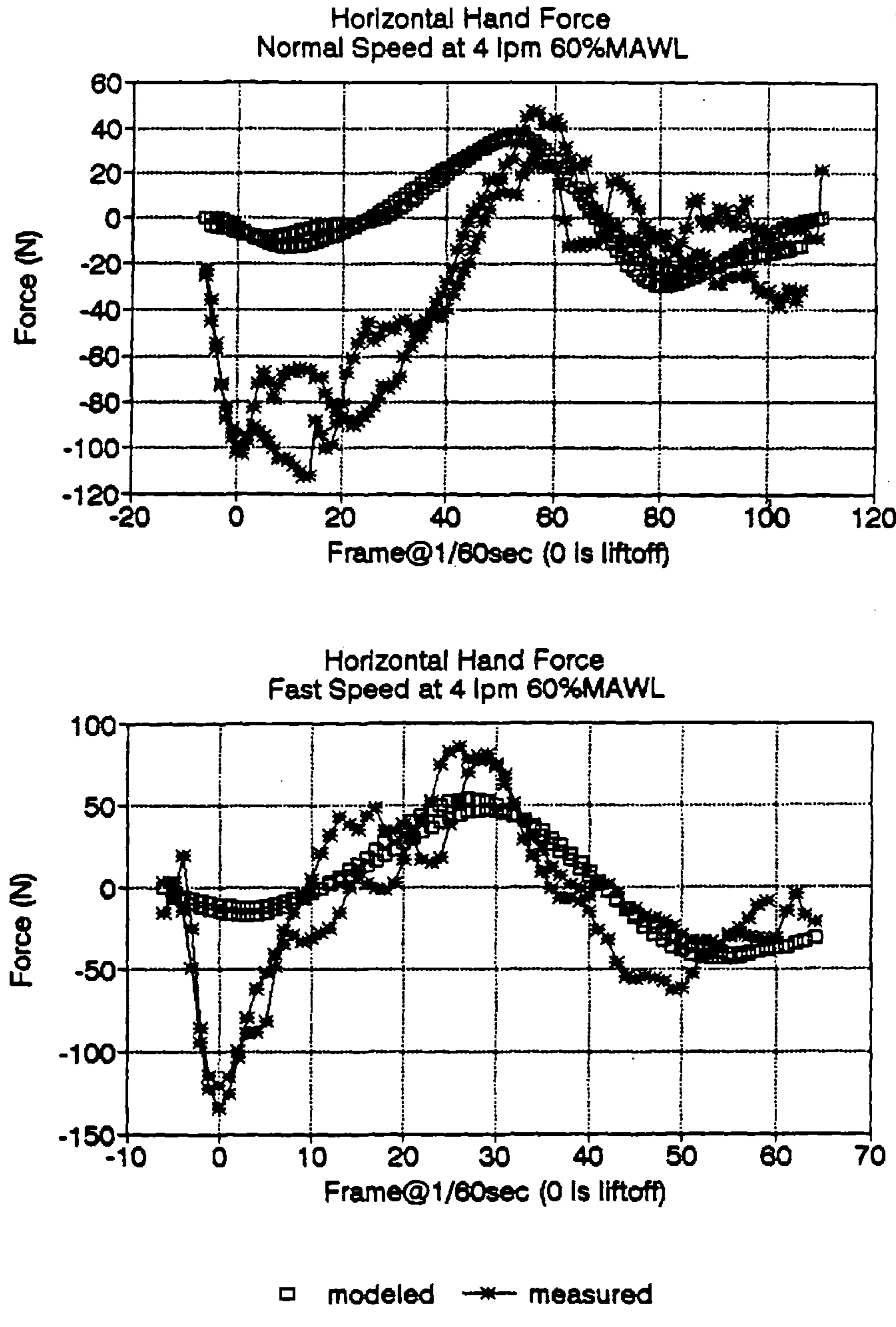


Figure 17. Plot of modeled and measured horizontal hand force for two trials at 4 lpm and 60% MAWL performed at normal (top) and fast (bottom) speeds.

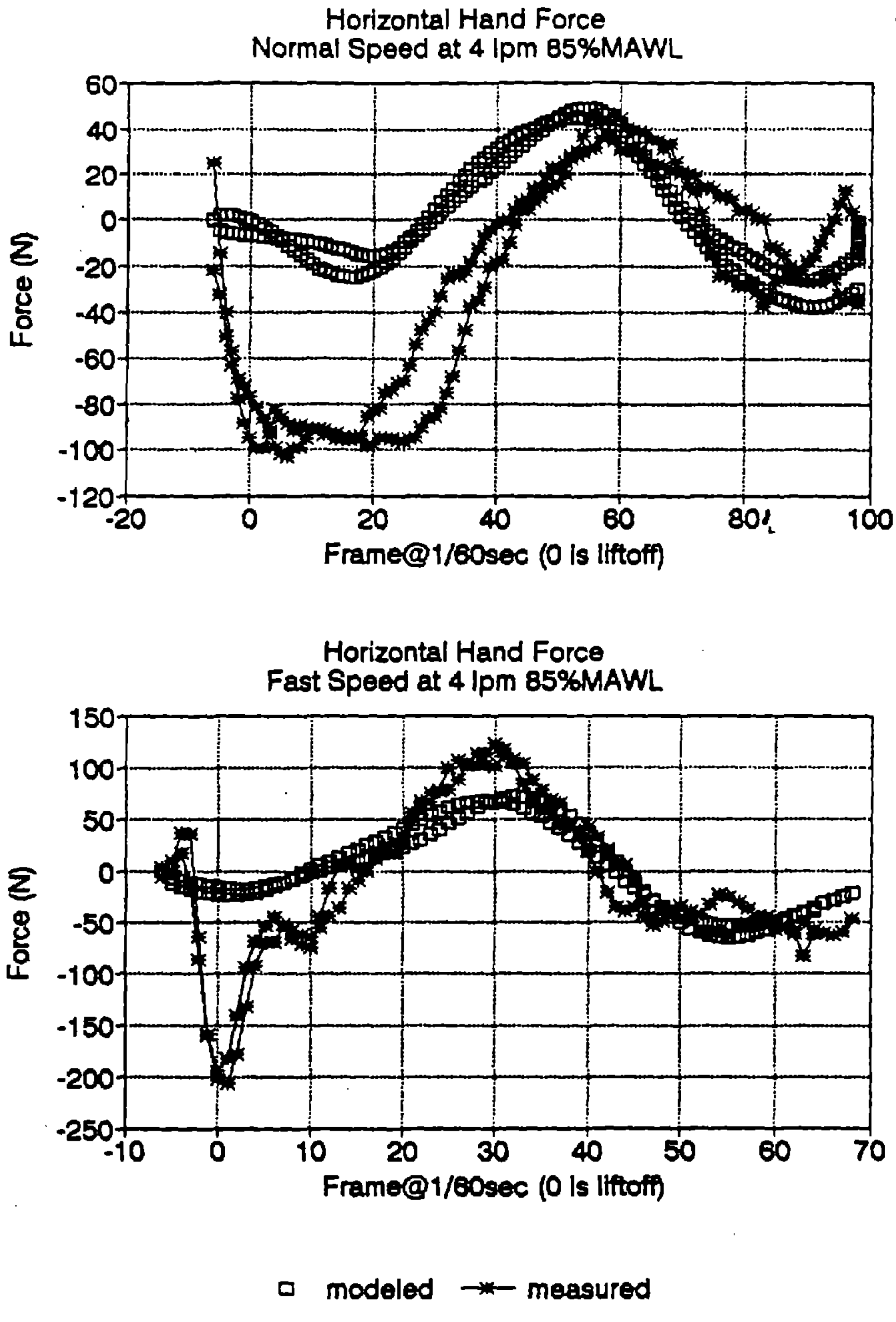


Figure 18. Plot of modeled and measured horizontal hand force for two trials at 4 lpm and 85% MAWL performed at normal (top) and fast (bottom) speeds.

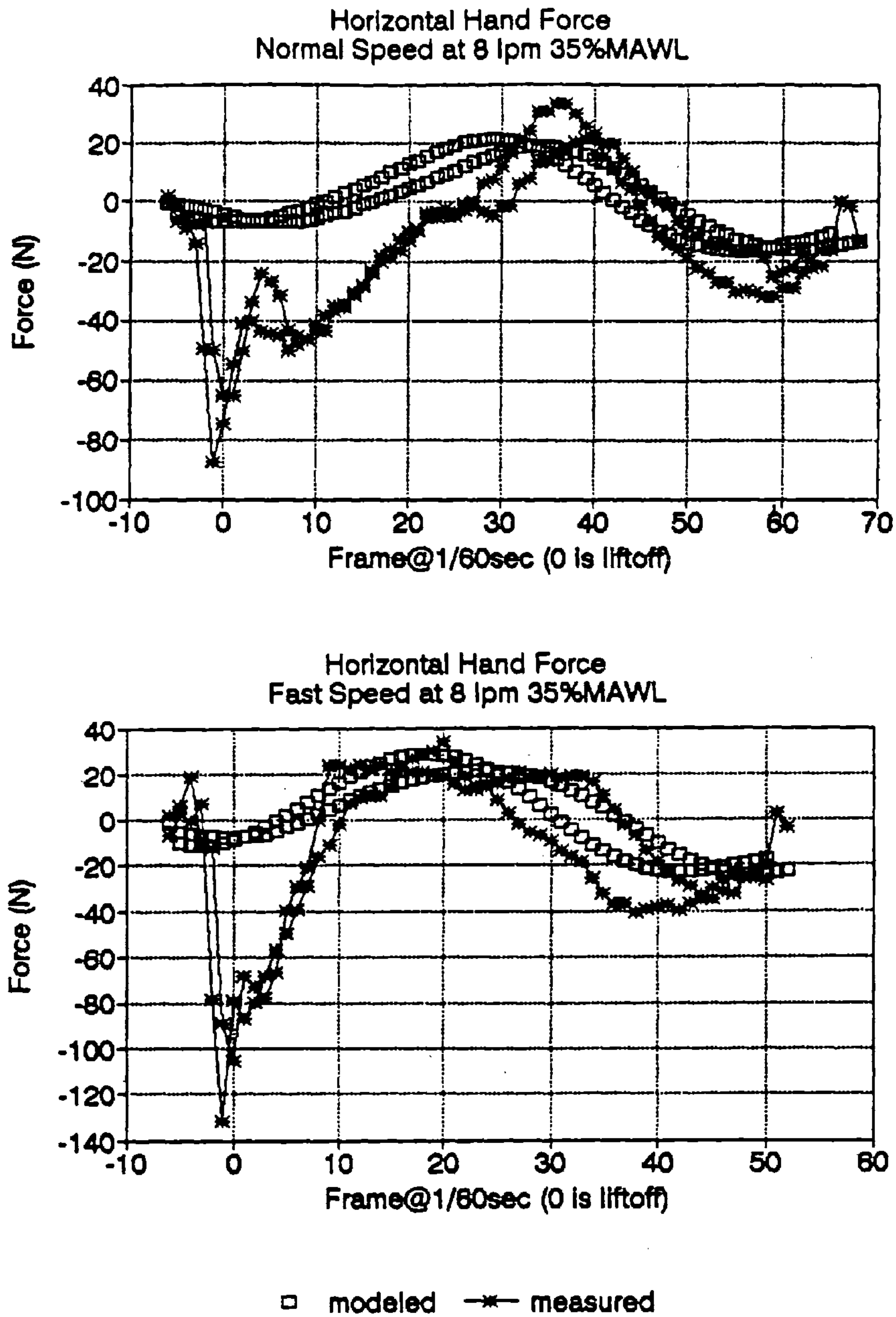


Figure 19. Plot of modeled and measured horizontal hand force for two trials at 8 lpm and 35% MAWL performed at normal (top) and fast (bottom) speeds.

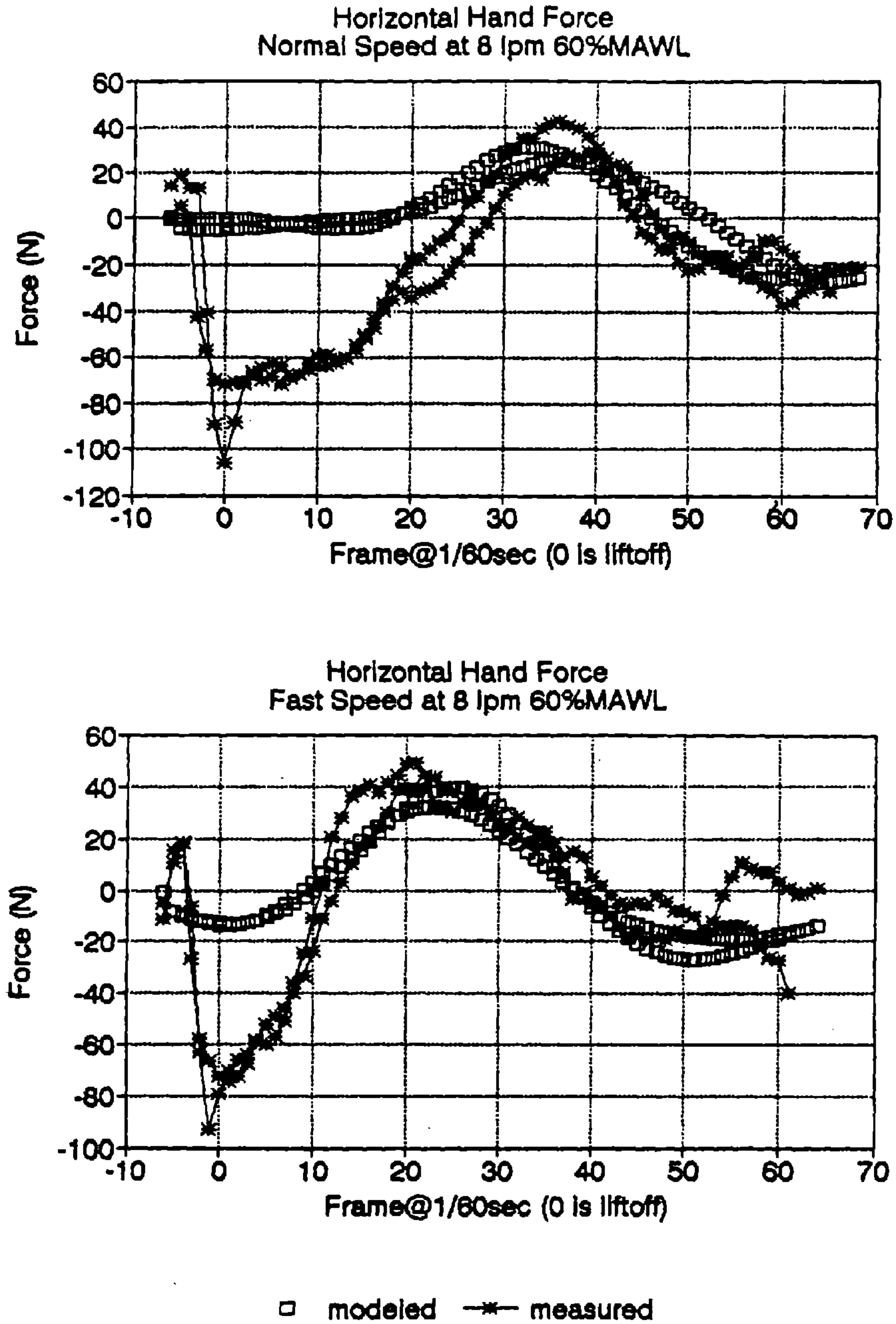


Figure 20. Plot of modeled and measured horizontal hand force for two trials at 8 lpm and 60% MAWL performed at normal (top) and fast (bottom) speeds.

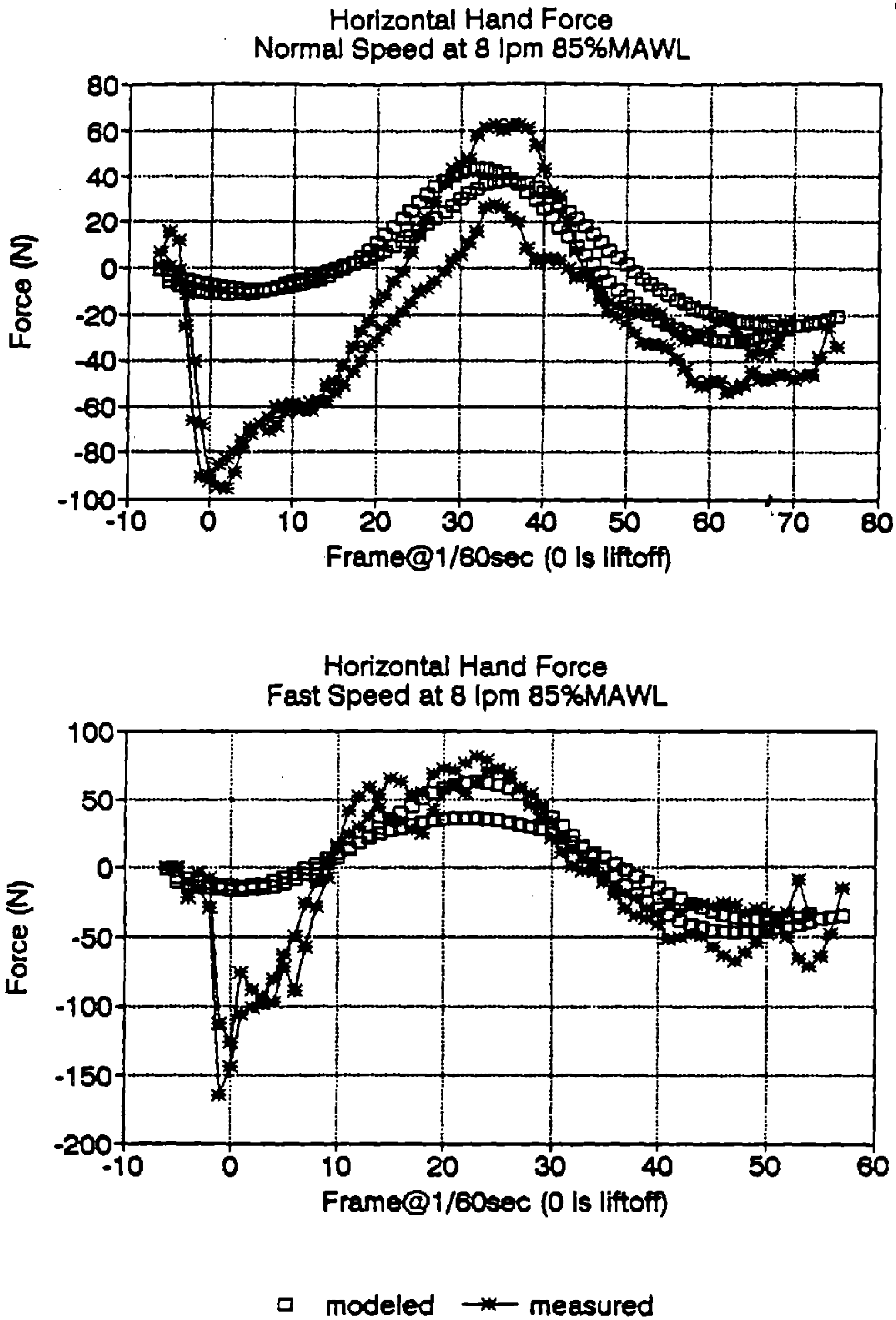


Figure 21. Plot of modeled and measured horizontal hand force for two trials at 8 lpm and 85% MAWL performed at normal (top) and fast (bottom) speeds.

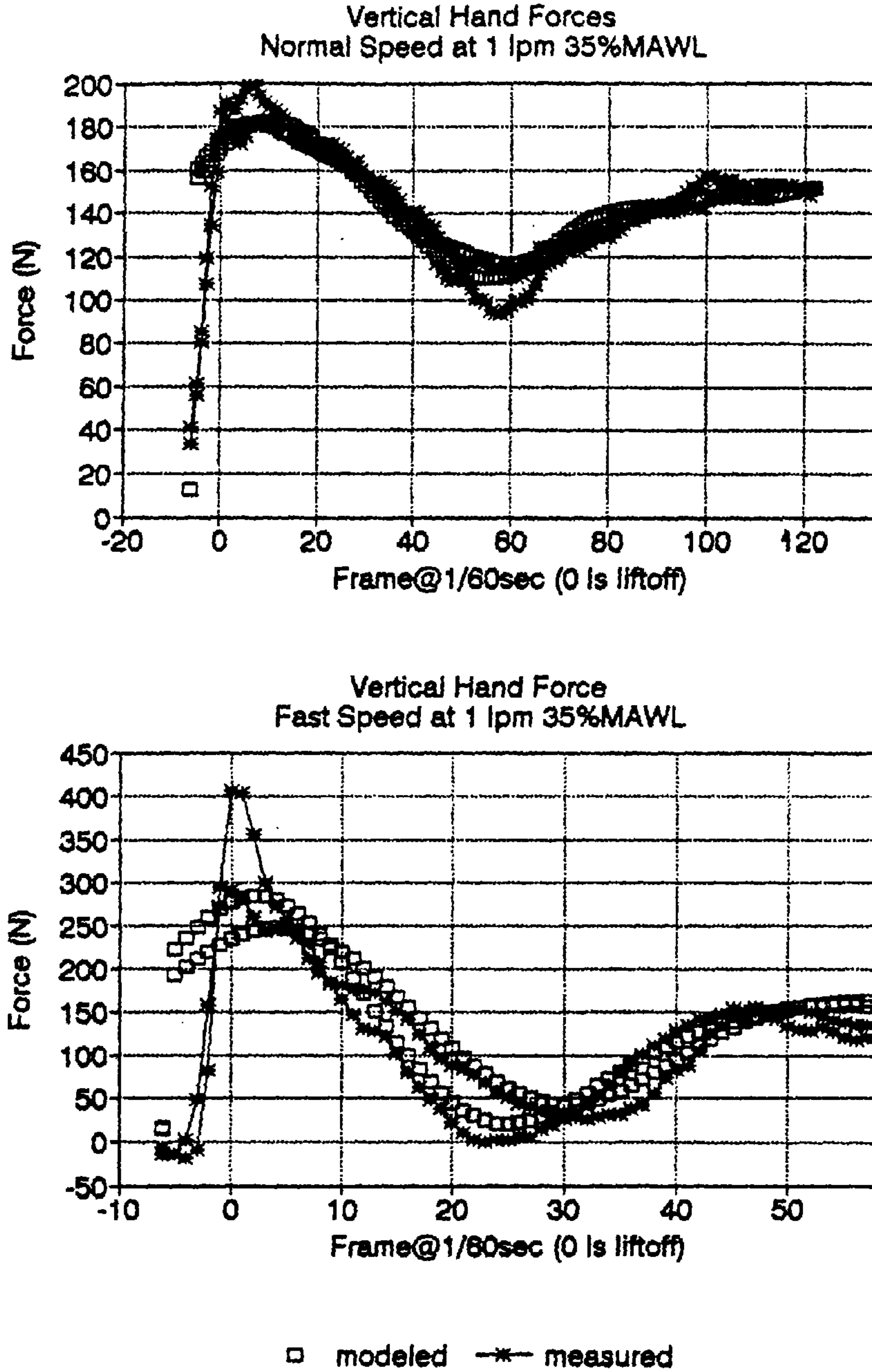


Figure 22. Plot of modeled and measured vertical hand force for two tri
at 1 lpm and 35% MAWL performed at normal (top) and fast (botto
speeds.

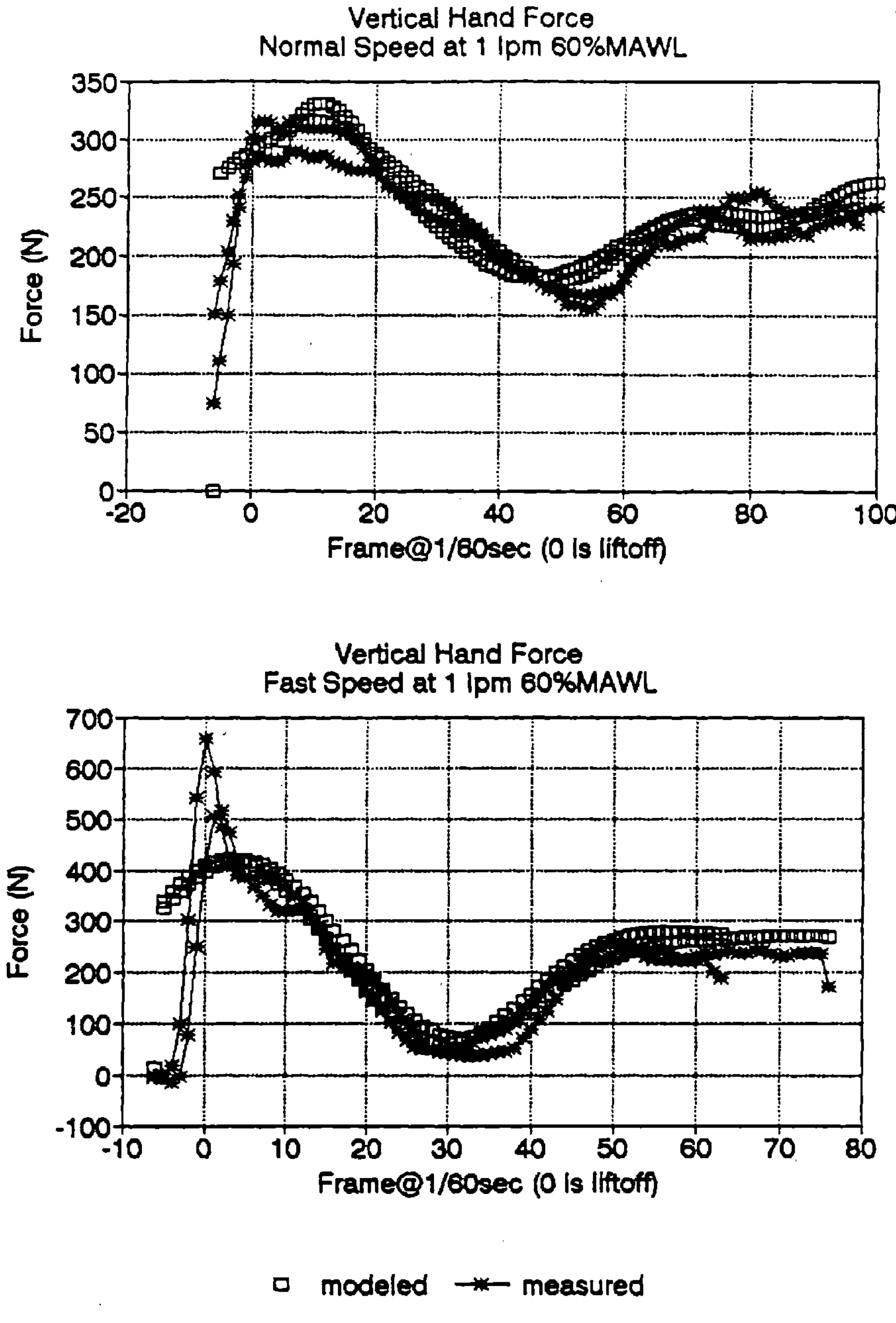
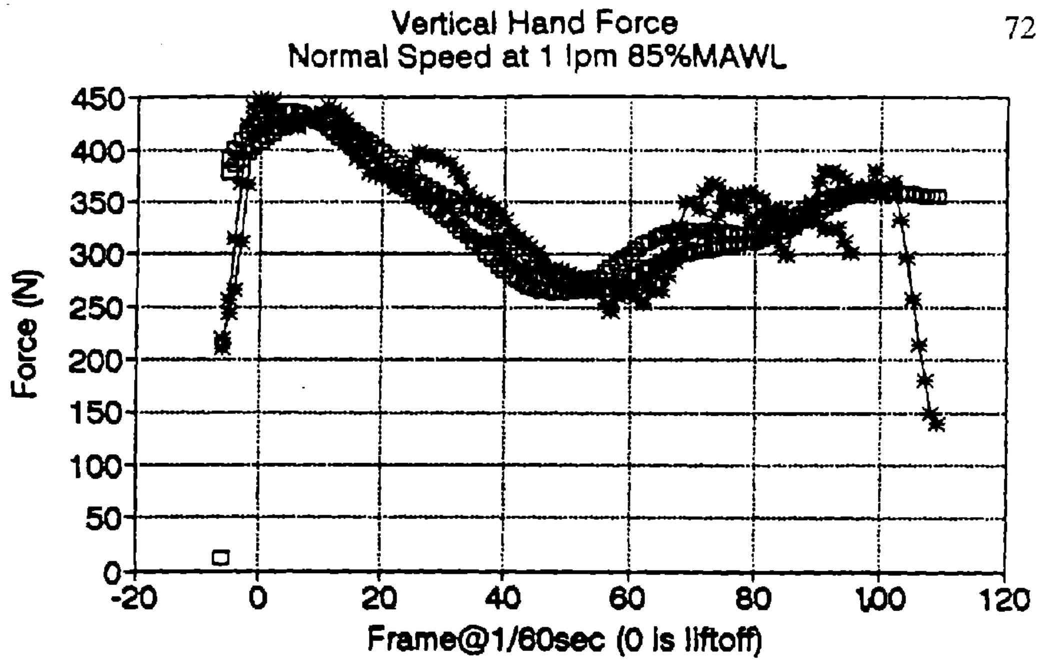


Figure 23. Plot of modeled and measured vertical hand force for two trials at 1 lpm and 60% MAWL performed at normal (top) and fast (bottom) speeds.



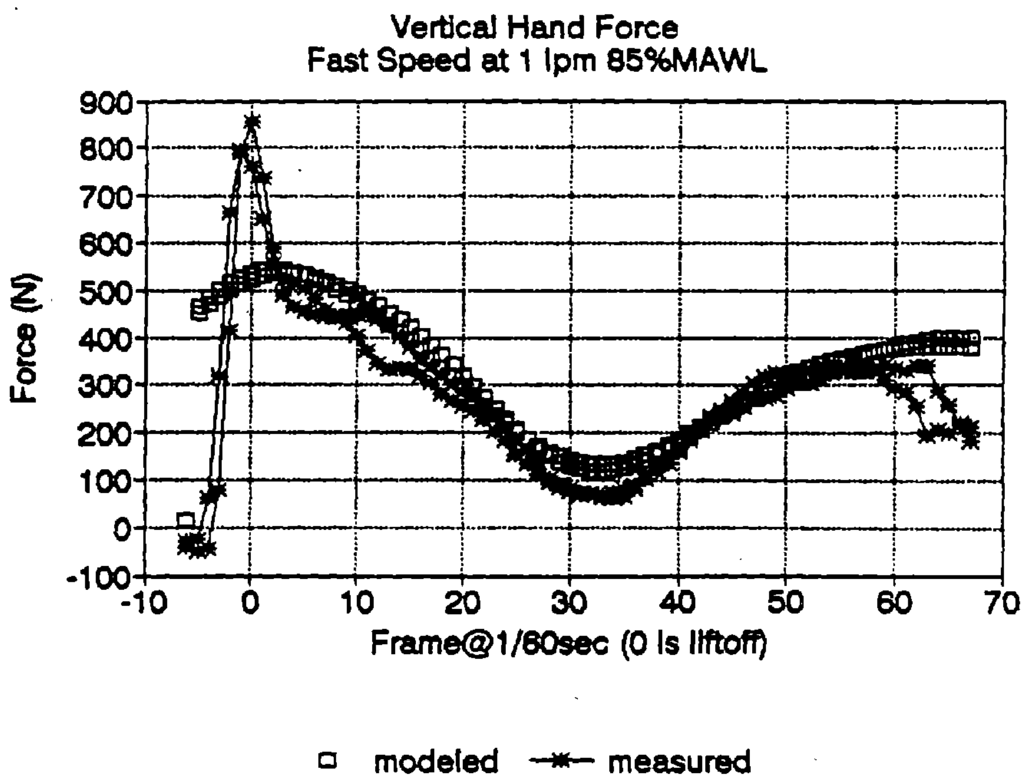
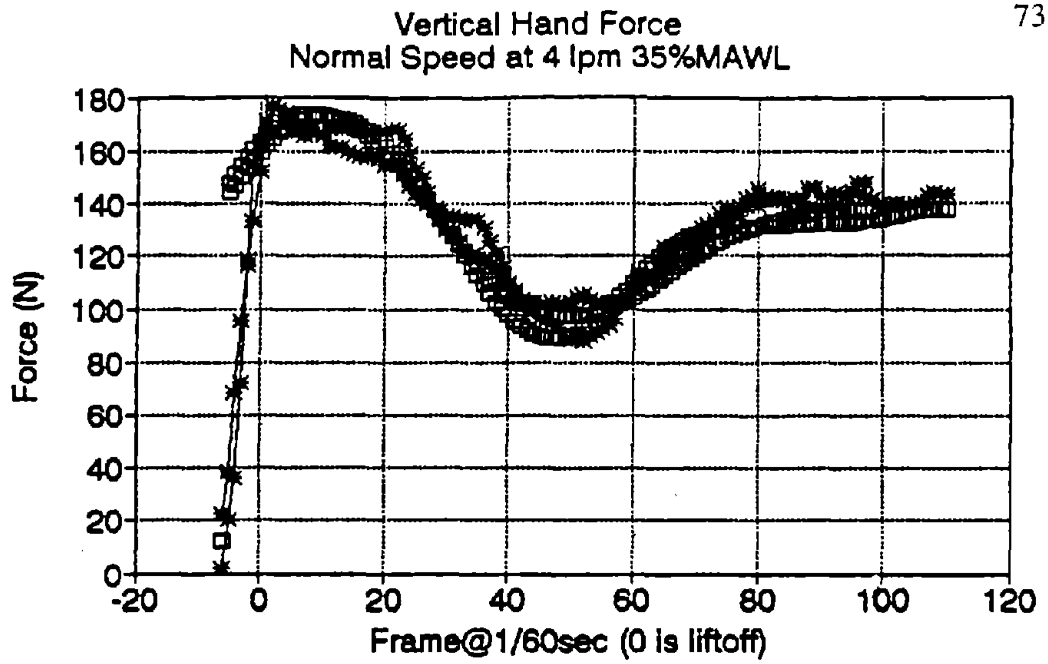


Figure 24. Plot of modeled and measured vertical hand force for two trials at 1 lpm and 85% MAWL performed at normal (top) and fast (bottom) speeds.



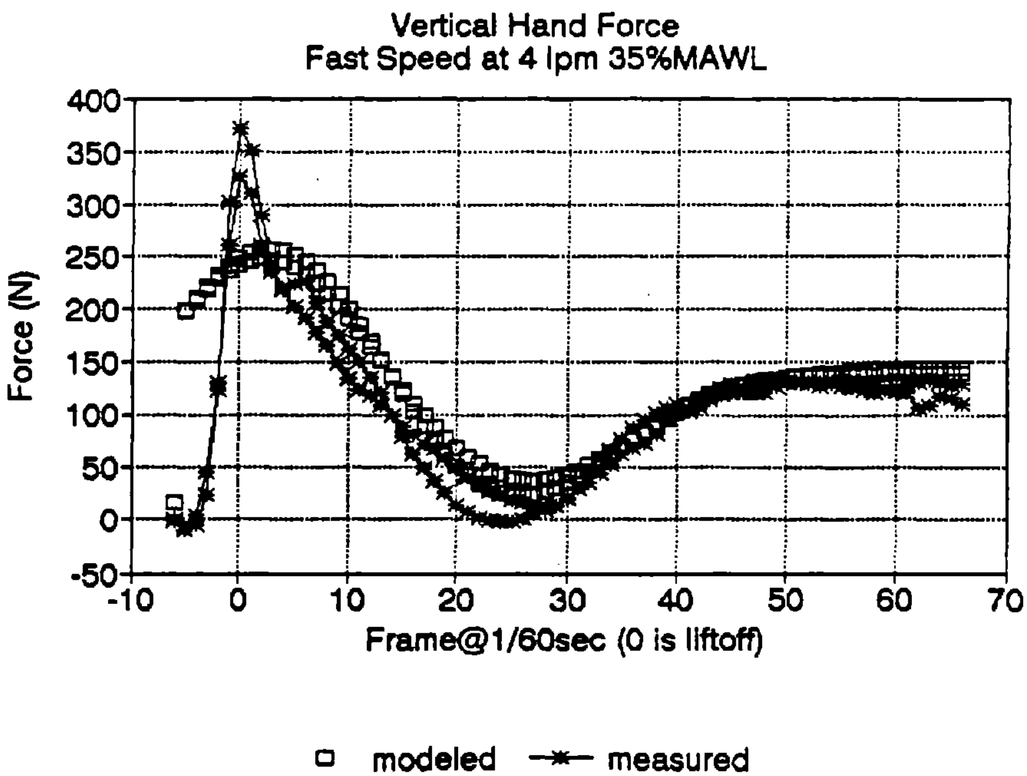


Figure 25. Plot of modeled and measured vertical hand force for two trials at 4 lpm and 35% MAWL performed at normal (top) and fast (bottom) speeds.

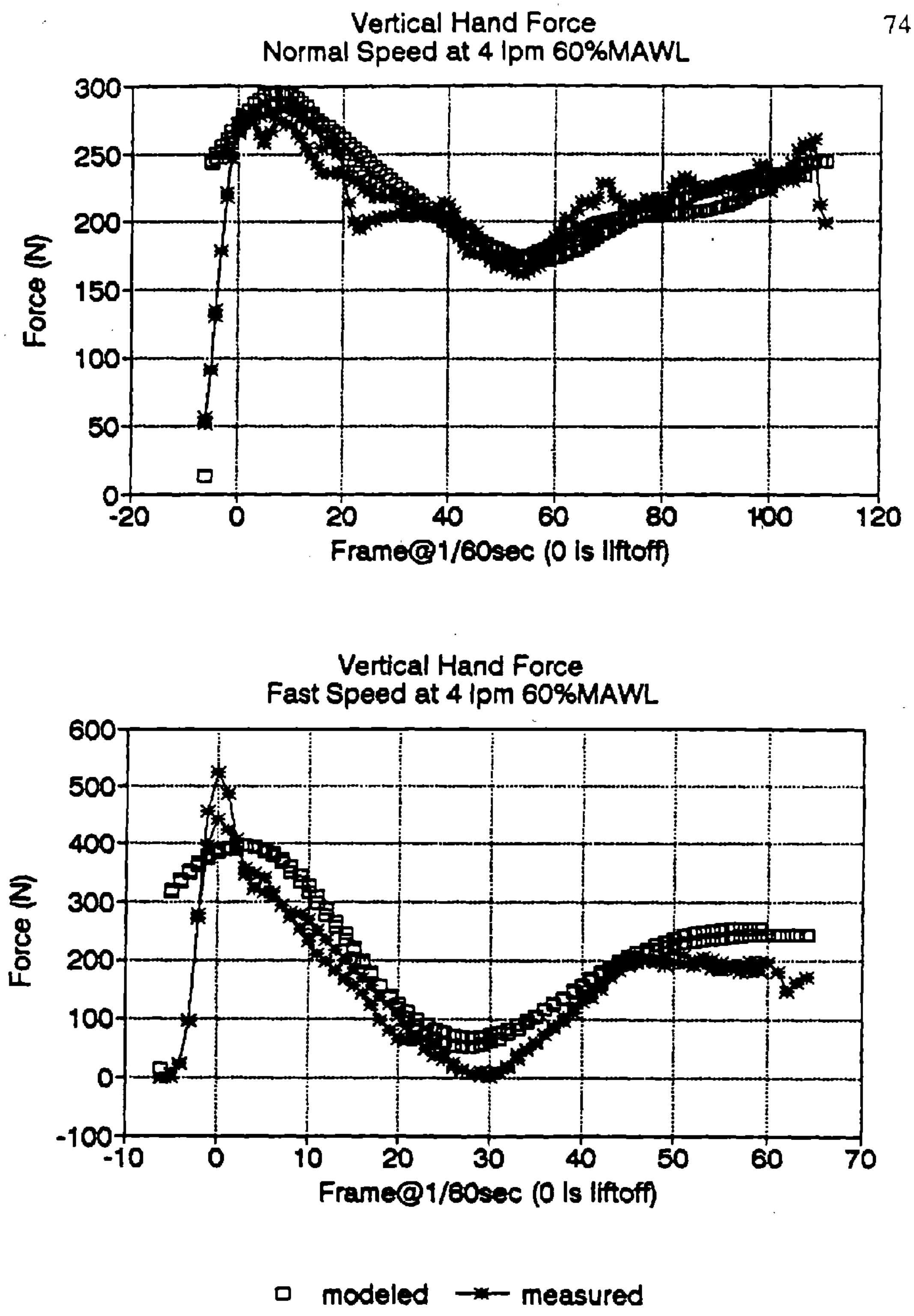


Figure 26. Plot of modeled and measured vertical hand force for two trials at 4 lpm and 60% MAWL performed at normal (top) and fast (bottom) speeds.

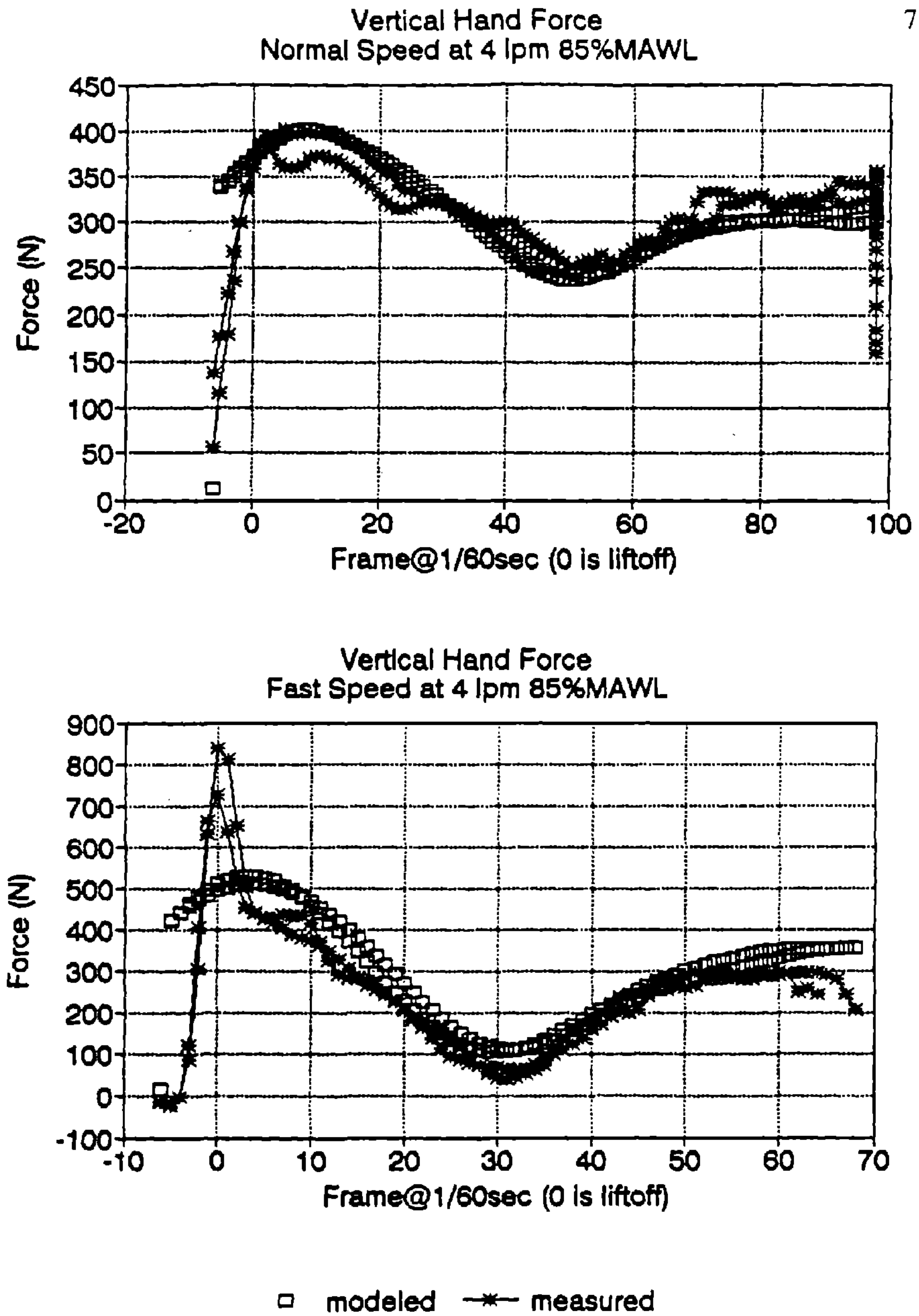


Figure 27. Plot of modeled and measured vertical hand force for two trials at 4 lpm and 85% MAWL performed at normal (top) and fast (bottom) speeds.

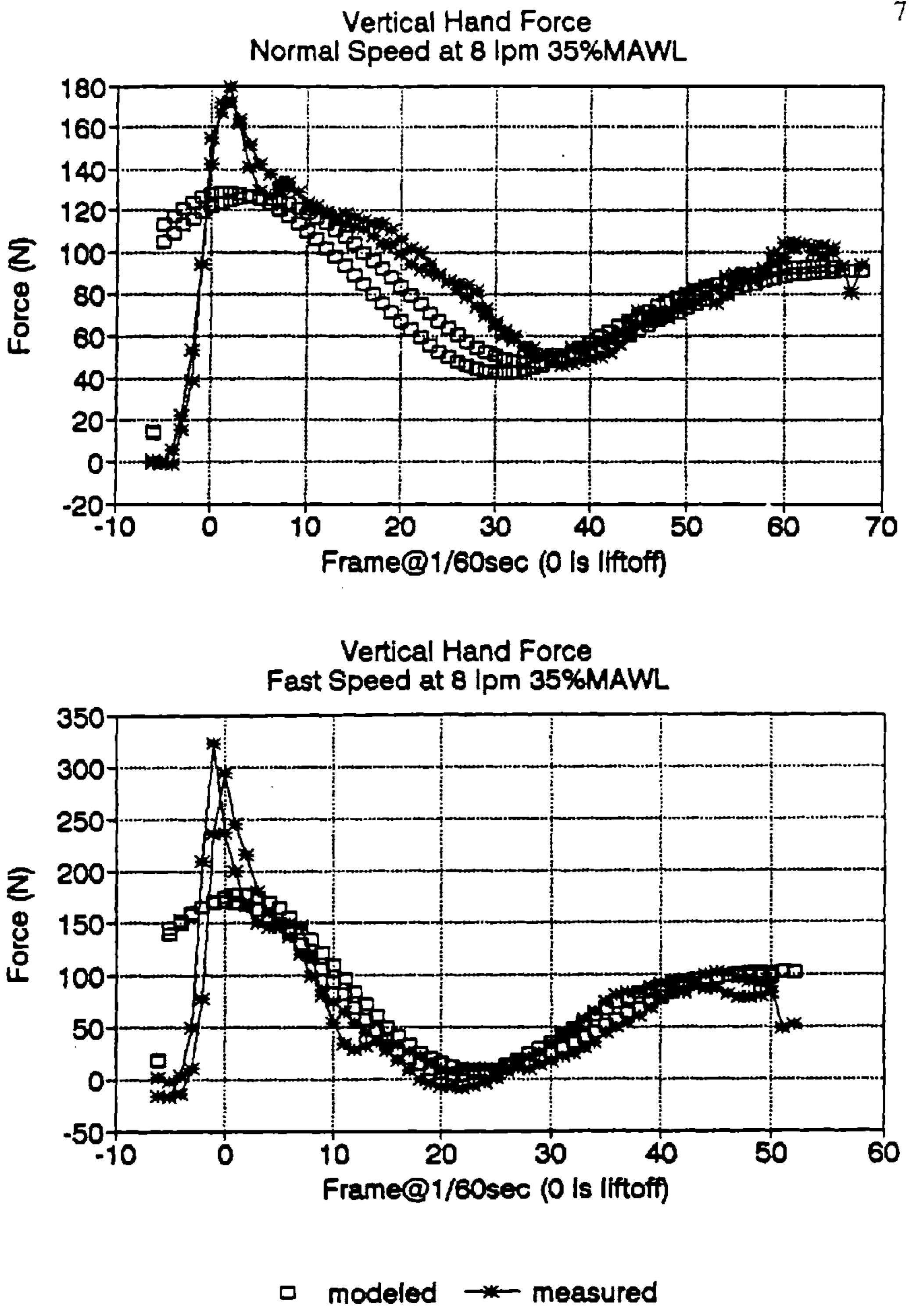


Figure 28. Plot of modeled and measured vertical hand force for two trials at 8 lpm and 35% MAWL performed at normal (top) and fast (bottom) speeds.

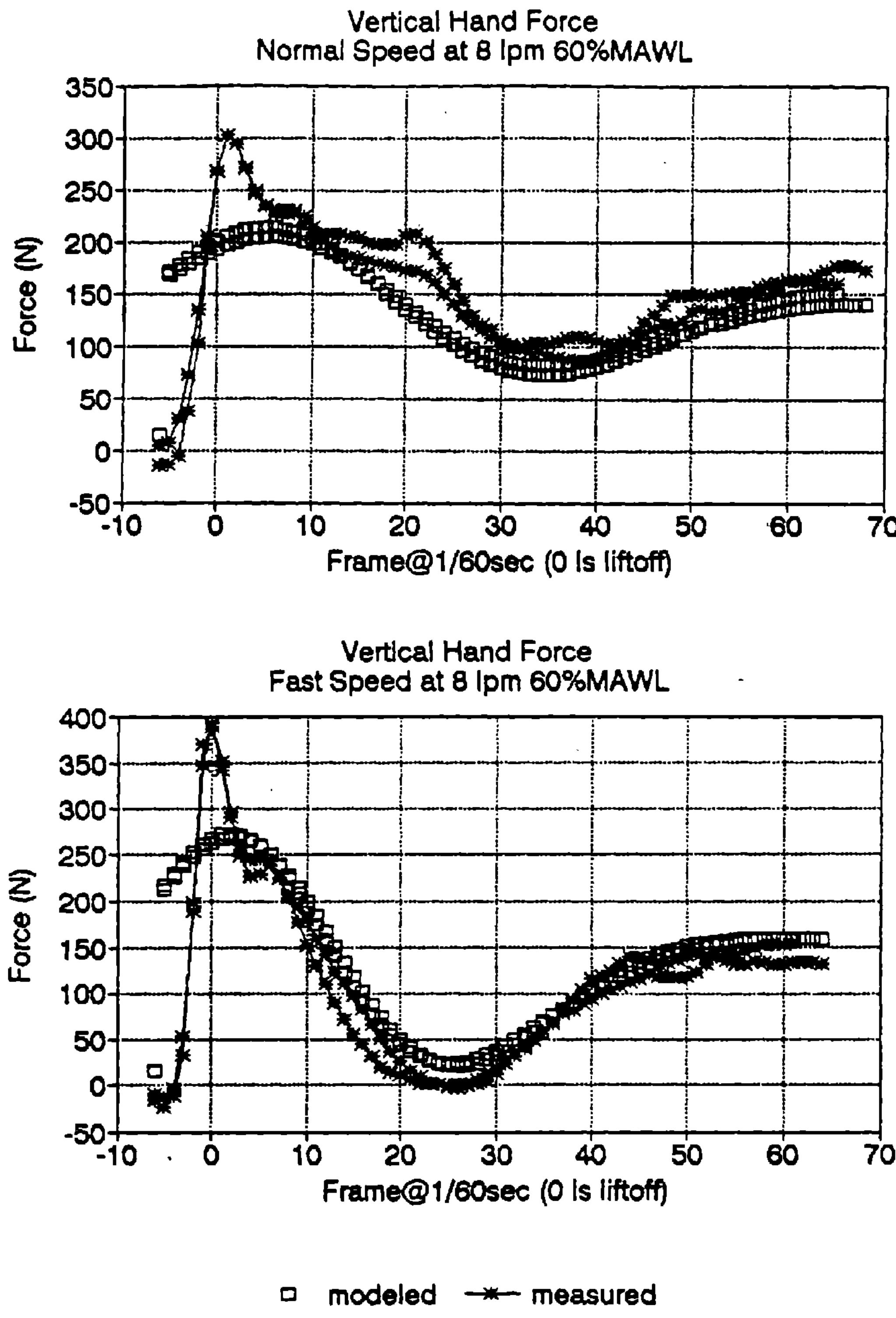


Figure 29. Plot of modeled and measured vertical hand force for two trials at 8 lpm and 60% MAWL performed at normal (top) and fast (bottom) speeds.

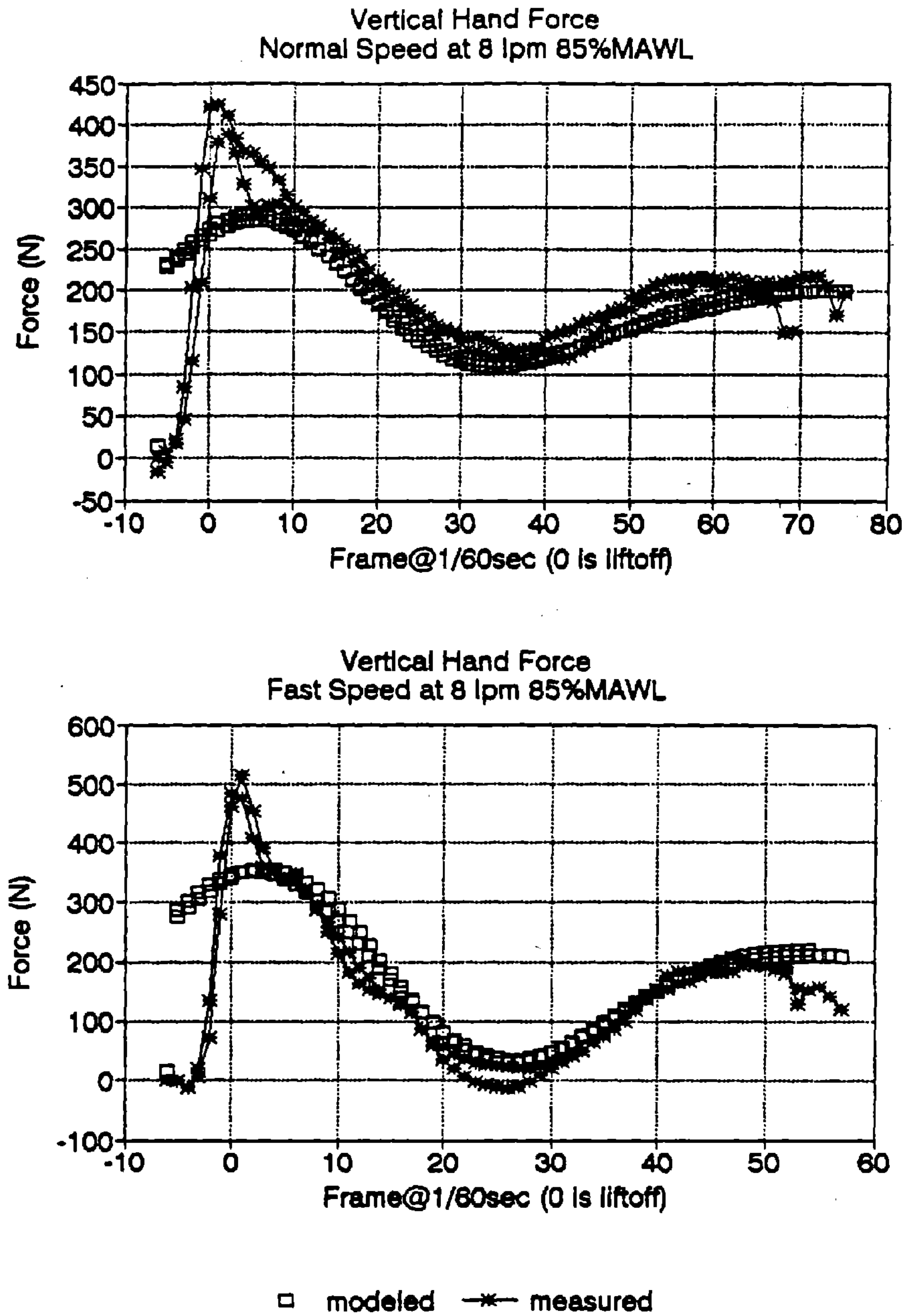


Figure 30. Plot of modeled and measured vertical hand force for two trials at 8 lpm and 85% MAWL performed at normal (top) and fast (bottom) speeds.

Tables 7 through 14 list mean, standard deviation, minimum and maximum values for the peak measured and calculated vertical and horizontal applied forces and resulting forces at L5/S1 for Experiments 1 and 2.

Modeled peak hand forces calculated by the Dynalift model were compared to the measured peak hand forces. Then the measured hand forces were input into the model and the resulting L5/S1 forces were compared to those modeled without the input of the measured hand forces. The results of the Dynalift biomechanical model for hand forces and L5/S1 forces were compared under Condition 1 (modeled hand forces) and Condition 2 (measured hand forces). Statistical analysis was performed by split plot design adding the "analysis" factor as a main effect. For all four force response variables the analysis effect was significant at .01 except for the compression of L5/S1 for Experiment 1. The summaries of the analysis factor is shown below in Table 15.

Paired t-tests on the means of the four response variables (vertical and horizontal applied forces and resulting compression and shear forces at L5/S1) compared modeled (Condition 1) and calculated (Condition 2) forces for fast and normal lifting speeds. The results are summarized in Table 16. The difference between all means were significant except for compressive force at L5/S1 calculated for the normal speed of lift for Experiments 1 and 2. For Experiment 1, the p value was .3010, and for Experiment 2 the p value was .1113. These values show that there were no significant differences between the means of the peak modeled (Condition 1) and modeled with measured input (Condition 2) compression forces at L5/S1 occurring during the pull phase of a normal speed lift.

Forces at L5/S1

Figures 31 through 39 are plots of L5/S1 compression calculated with the measured and modeled hand forces for two trials of each of the nine lifting tasks for a single subject performing at normal and fast speeds. Figures 40 through 48 are plots of L5/S1 shear

Table 7. Comparison of mean vertical peak applied forces (N) by the hands during the pull stage of the lift for Conditions 1 (model) and 2 (measured input to model) by speed, frequency, and %MAWL for Experiment 1.

Freq (lpm)	MAWL (%)		Lifting Speed							
			Normal				Fast			
			Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
	35	1	173	38	128	241	229	46	169	292
		2	206	61	152	343	362	82	262	475
1	60	1	273	59	213	355	369	57	304	432
		2	328	80	223	470	585	146	406	828
	85	1	384	76	298	494	467	65	377	544
		2	418	128	276	635	727	203	488	1045
	35	1	136	22	111	174	196	32	160	258
		2	156	26	122	183	287	68	198	372
4	60	1	221	40	180	296	306	53	243	397
		2	252	42	177	294	444	144	297	753
	85	1	315	49	251	402	400	68	323	532
		2	381	56	275	463	560	138	371	842
	35	1	101	15	88	129	131	23	112	177
		2	129	29	85	180	204	60	137	323
8	60	1	169	24	144	214	209	33	180	273
		2	216	51	146	303	294	63	217	394
	85	1	228	34	201	293	277	44	234	357
		2	304	61	232	424	421	62	336	515

Table 8. Comparison of mean horizontal peak applied forces (N) by the hands during the pull stage of the lift for Conditions 1 (model) and 2 (measured input to model) by speed, frequency, and %MAWL for Experiment 1. The negative sign indicates that direction of force originated at the load and was directed toward the lifter's body.

Freq (lpm)	MAWL (%)		Lifting Speed: Normal Mean	Normal S.D.	Normal Min	Normal Max	Fast Mean	Fast S.D.	Fast Min	Fast Max
	35	1	-7	4	-15	-2	-19	10	-37	-7
		2	-56	21	-84	-25	-116	49	-198	-55
1	60	1	-10	5	-18	-4	-28	10	-43	-13
		2	-87	42	-136	-36	-203	75	-355	-108
	85	1	-14	7	-27	-7	-381	18	-74	-11
		2	-140	83	-249	-34	-253	52	-311	-173
	35	1	-5	2	-8	-2	-16	6	-27	-8
		2	-44	22	-78	-22	-107	21	-138	-71
4	60	1	-9	2	-13	-5	-19	8	-31	-3
		2	-71	37	-130	-32	-128	54	-283	-51
	85	1	-15	11	-36	-0.1	-28	8	-43	-18
		2	-104	58	-237	-41	-178	45	-227	-105
	35	1	-6	2	-7	-1	-10	2	-15	-7
		2	-39	24	-88	-10	-78	30	-131	-36
8	60	1	-6	3	-14	-3	-16	7	-27	-6
		2	-58	32	-106	-18	-96	21	-132	-68
	85	1	-10	5	-17	-3	-17	8	-32	-7
		2	-93	24	-137	-61	-148	44	-24.90	-95

Table 9. Comparison of mean peak L5/S1 compression forces (N) during the pull stage of the lift for Conditions 1 (from model) and 2 (measured input to model) by speed, frequency, and %MAWL for Experiment 1.

Freq (lpm)	MAWL (%)		Lifting Speed Normal Mean	S.D.	Min	Max	Fast Mean	S.D.	Min	Max
	35	1	5611	768	4359	6572	6538*	1340	4249	8483
		2	5649	785	4316	6602	7117*	1566	4212	9026
1	60	1	6836*	1018	5249	8250	7876*	630	6988	8904
		2	7136*	1628	5452	10447	8463*	703	7333	9622
	85	1	6831*	1254	5165	8557	7668*	1645	4819	9651
		2	6642*	1127	5238	8107	8543*	2054	5412	11022
	35	1	5210	821	4173	6631	6674*	1058	5093	8236
		2	5184	725	4168	6370	6986*	1222	5070	8646
4	60	1	6421*	997	5338	7811	7651*	807	6823	8987
		2	6400*	1097	5197	8461	8366*	1007	6867	9516
	85	1	6499*	1063	5028	8243	7813*	940	7047	9471
		2	6434*	962	4949	7941	8295*	1081	7500	10681
	35	1	5328	711	4494	6641	6093*	1119	4532	7961
		2	5428	737	4545	6756	6334*	1217	4609	8415
8	60	1	6238	1198	5009	8143	6988*	843	5968	8476
		2	6421*	1412	4959	8507	7470*	986	6627	8930
	85	1	6625*	874	5692	7923	7243*	913	5899	8815
		2	6801*	1057	5564	8551	7647*	990	6491	9344

* Compression force is above the 637 kg maximum tolerance limit as defined by Jager and Luttman (1989) or 650 kg specified by NIOSH (1981).

Table 10. Comparison of mean peak L5/S1 shear forces (N) during the pull stage of the lift for Conditions 1 (model) and 2 (measured input to model) by speed, frequency, and %MAWL for Experiment 1.

Freq (lpm)	MAWL (%)		Lifting Speed Normal Mean	Normal S.D.	Normal Min	Normal Max	Fast Mean	Fast S.D.	Fast Min	Fast Max
	35	1	534	152	268	708	639	215	317	880
		2	567	154	313	774	731	271	348	1132
1	60	1	694	99	561	807	816	129	678	983
		2	808	200	574	1227	964	144	754	1186
	85	1	697	198	320	898	774	261	317	1047
		2	734	181	394	945	968	384	191	1366
	35	1	509	145	283	672	631	211	305	860
		2	526	141	294	695	708	234	300	982
4	60	1	641	114	506	794	791	128	586	950
		2	662	116	503	812	939	158	613	1128
	85	1	645	199	345	878	832	168	640	1049
		2	687	227	251	921	1003	217	721	1393
	35	1	493	118	337	683	577	186	328	815
		2	532	126	388	741	648	226	362	983
8	60	1	616	113	451	729	668	165	448	899
		2	678	156	435	853	766	175	556	1020
	85	1	652	119	480	787	714	196	371	931
		2	722	138	593	927	823	251	387	1095

Table 11. Mean, standard deviation and range of the peak applied forces (N) in vertical direction during the pull phase by speed and load under Conditions 1 (model) and 2 (measured input to model) for Experiment 2.

		Lifting Speed							
Load (kg)		Normal				Fast			
		Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
6.25	1	102	8	94	115	138	11	119	154
	2	122	26	95	168	218	36	16	256
10.91	1	178	54	141	328	216	19	195	247
	2	221	50	165	292	369	87	259	525
15.45	1	223	12	210	247	289	20	252	320
	2	281	58	197	360	505	121	273	706
20.00	1	277	21	220	294	355	22	324	396
	2	369	58	293	490	610	154	410	942
24.77	1	347	15	330	365	416	33	362	463
	2	474	110	322	665	742	183	523	1062

Table 12. Mean, standard deviation and range of the peak applied forces (N) in horizontal direction during the pull phase by speed and load under Conditions 1 (model) and 2 (measured input to model) for Experiment 2. The negative sign indicates that direction of force originated at the load and was directed toward the lifter's body.

		Lifting Speed							
Load (kg)		Normal				Fast			
		Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
6.25	1	-6	1	-8	-4	-15	5	-24	-11
	2	-34	15	-68	-17	-72	19	-102	-51
10.91	1	-9	3	-13	-4	-23	7	-38	-15
	2	-50	15	-72	-30	-114	26	-164	-90
15.45	1	-13	5	-19	-4	-27	8	-38	-15
	2	-67	19	-104	-45	-144	30	-198	-104
20.00	1	-16	6	-27	-9	-29	8	-39	-17
	2	-90	22	-125	-51	-163	57	-288	-99
24.77	1	-19	5	-31	-14	-33	12	-51	-15
	2	-131	50	-243	-91	-244	76	-364	-120

Table 13. Mean, standard deviation and range of the peak L5/S1 compression (N) during the pull phase by speed and load under Conditions 1 (model) and 2 (measured input to model) for Experiment 2.

		Lifting Speed							
Load (kg)		Normal				Fast			
		Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
6.25	1	5626	735	4693	6988	6846*	957	5693	8202
	2	5586	661	4565	6694	7201*	915	5860	8502
10.91	1	6149	881	4702	7420	7308 *	826	6192	8669
	2	6265	831	4746	7038	8114 *	1234	6669	10388
15.45	1	6468*	726	5482	7952	7644*	797	6610	8995
	2	6604 *	541	5713	7372	8753 *	1280	6843	10977
20.00	1	6819*	596	6117	7853	7856 *	735	6952	9307
	2	7045*	822	6037	8445	9137*	1412	7712	12408
24.77	1	7086 *	733	6202	8384	8372*	844	7252	9904
	2	7623*	827	6314	8977	9957 *	2181	8134	14184

* Compression force is above the 637 kg maximum tolerance limit as defined by Jager and Luttman (1989) or 650 kg specified by NIOSH (1981).

Table 14. Mean, standard deviation and range of the peak L5/S1 shear (N) during the pull phase by speed and load under Conditions 1 (model) and 2 (measured input to model) for Experiment 2.

		Lifting Speed							
Load (kg)		Normal				Fast			
		Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
6.25	1	498	134	328	670	655	139	458	847
	2	520	133	397	703	719	148	522	902
10.91	1	575	129	377	731	718	136	530	882
	2	612	148	410	820	855	202	602	1152
15.45	1	598	149	376	779	760	141	560	950
	2	639	110	450	759	968	213	651	1300
20.00	1	655	144	447	833	793	143	634	1014
	2	694	137	474	865	1035	262	755	1512
24.77	1	701	183	414	931	837	164	602	1079
	2	694	221	295	938	1141	292	752	1564

Table 15. Significance of type of analysis: modeled (condition 1) and measured (condition 2) effect on the mean peak forces (N) for experiments 1 and 2.

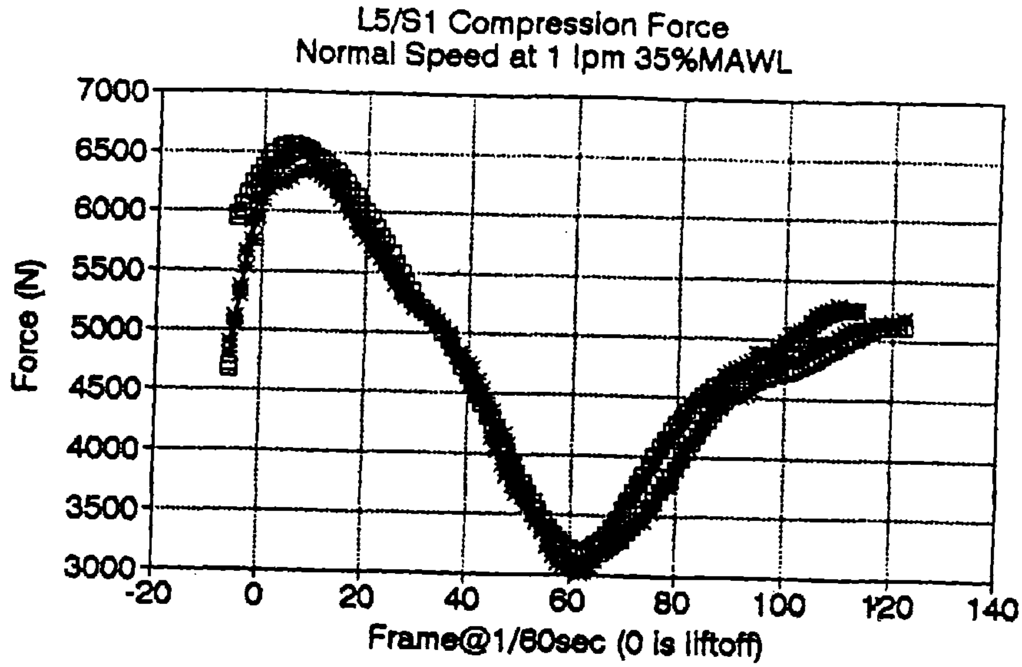
Force	Source	df	Type III SS	F Value	PR>F
Experiment 1					
Vertical Applied	Analysis	1	8314.96	35.22	.0040 *
Horizontal Applied	Analysis	1	8635.47	76.88	.0009 *
Shear at L5/S1	Analysis	1	6886.60	23.92	.0081 *
Comp at L5/S1	Analysis	1	77546.22	5.16	.0855
Experiment 2					
Vertical Applied	Analysis	1	194378.62	16.32	.0156 *
Horizontal Applied	Analysis	1	6159.83	51.56	.0097 *
Shear at L5/S1	Analysis	1	9762.24	111.77	.0005 *
Comp at L5/S1	Analysis	1	4381.51	182.18	.0002 *

* $p \leq .05$

Table 16. Paired t-tests on the Means of the Response Variables for Normal and Fast Speeds of Lift for Modeled with Measured Input for Experiments 1 and 2.

Response Variable	Speed of Lift					
	Normal			Fast		
	df	t value	p	df	t value	p
Experiment 1						
Vertical Applied	8	7.089	.0001 *	8	7.023	.0001 *
Horizontal Applied	8	7.033	.0001 *	8	7.688	.0001 *
Shear at L5/S1	8	4.854	.0013 *	8	8.481	.0001 *
Comp at L5/S1	8	1.106	.3010	8	7.943	.0001 *
Experiment 2						
Vertical Applied	4	3.590	.0230 *	4	4.884	.0081 *
Horizontal Applied	4	4.197	.0137 *	4	3.442	.0263 *
Shear at L5/S1	4	2.948	.0420 *	4	4.563	.0103 *
Comp at L5/S1	4	2.037	.1113	4	4.887	.0081 *

* $p \leq .05$



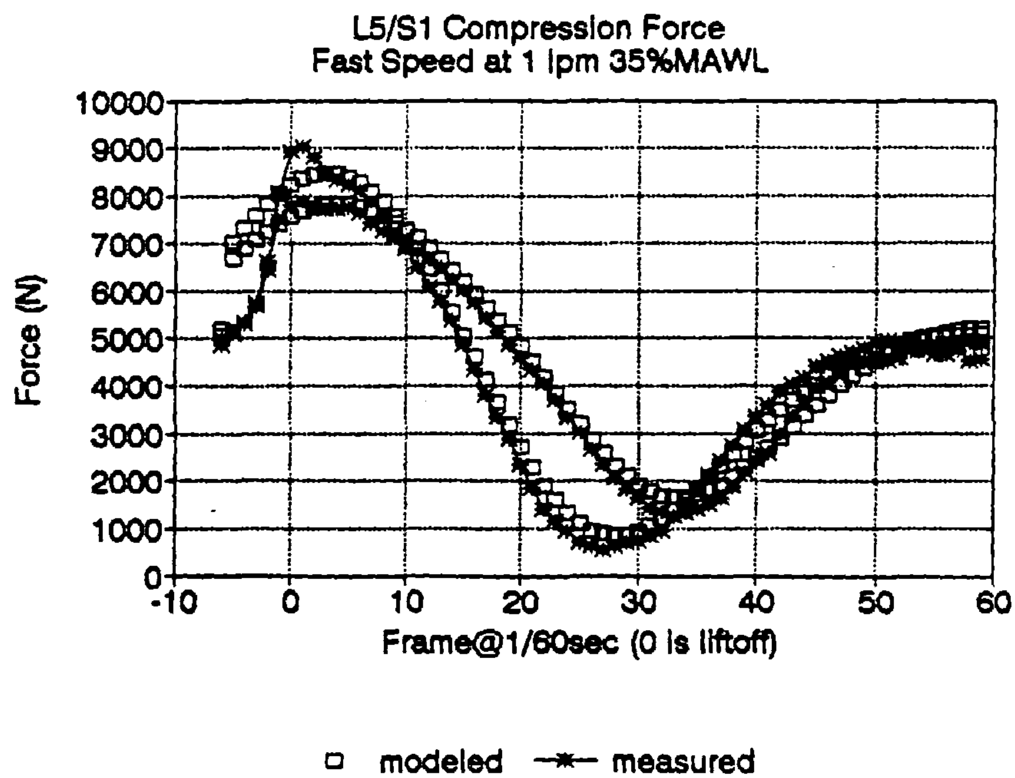


Figure 31. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 1 lpm and 35%MAWL performed at normal (top) and fast (bottom) speeds.

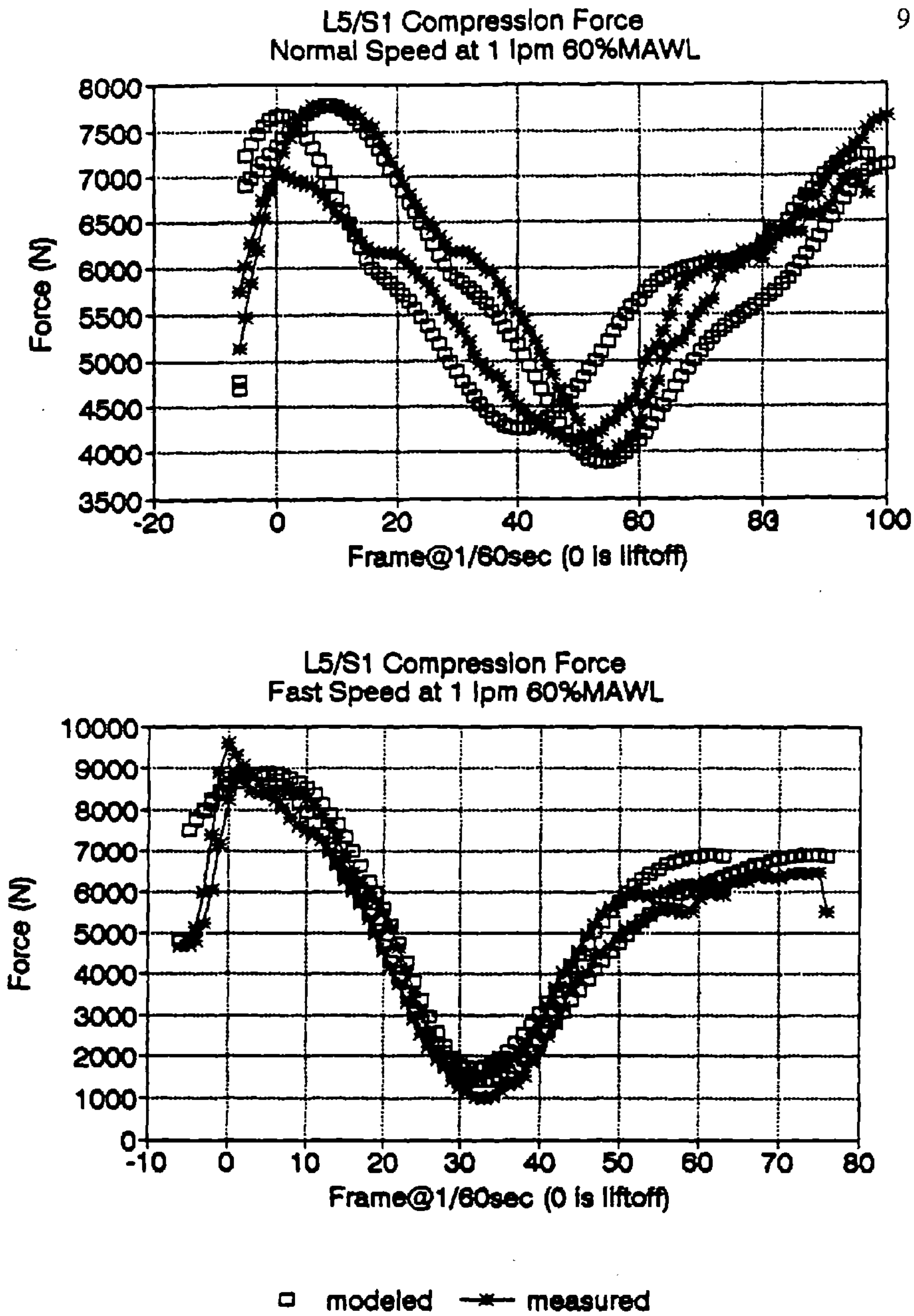


Figure 32. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 1 lpm and 60%MAWL performed at normal (top) and fast (bottom) speeds.

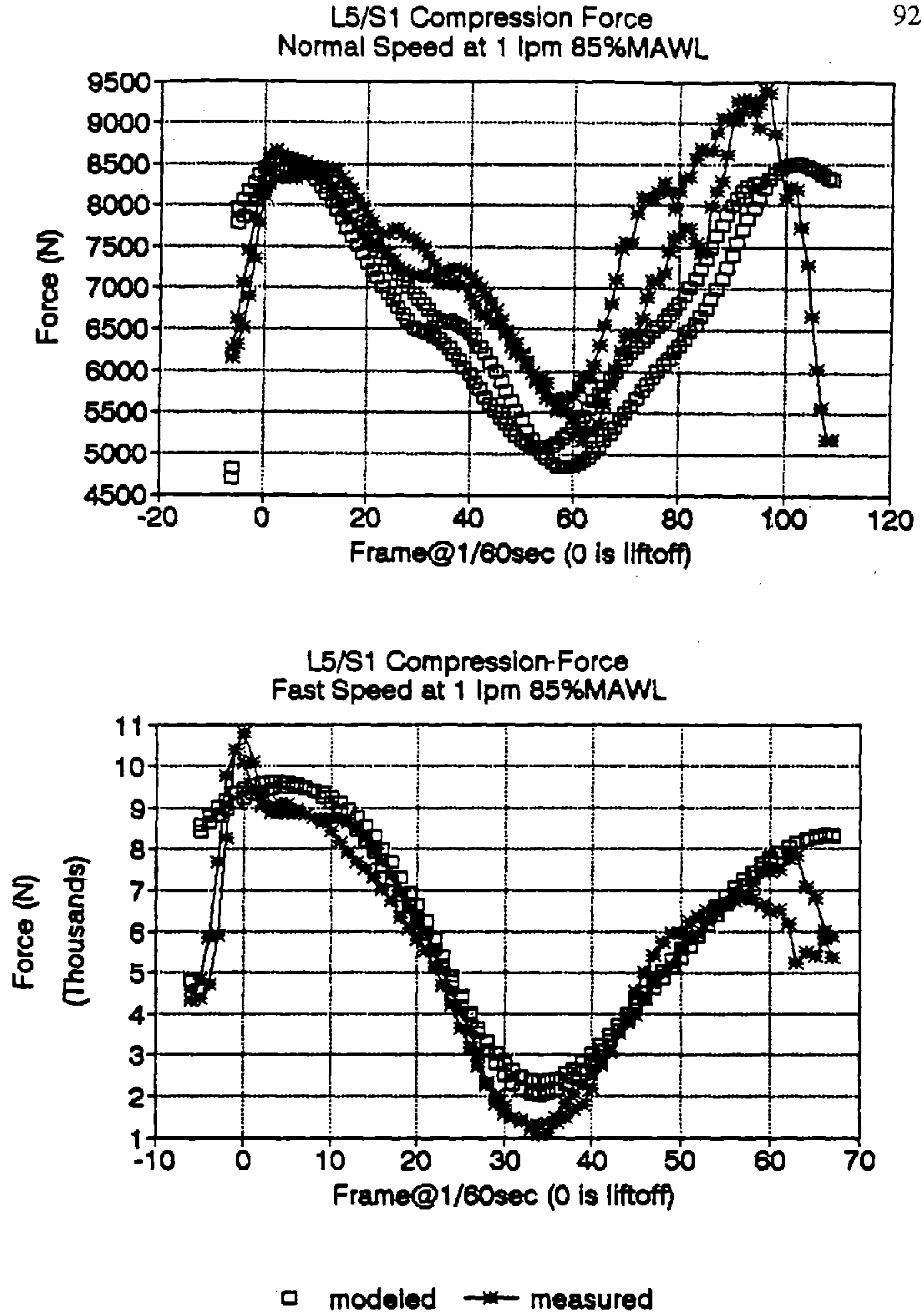


Figure 33. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 1 lpm and 85%MAWL performed at normal (top) and fast (bottom) speeds.

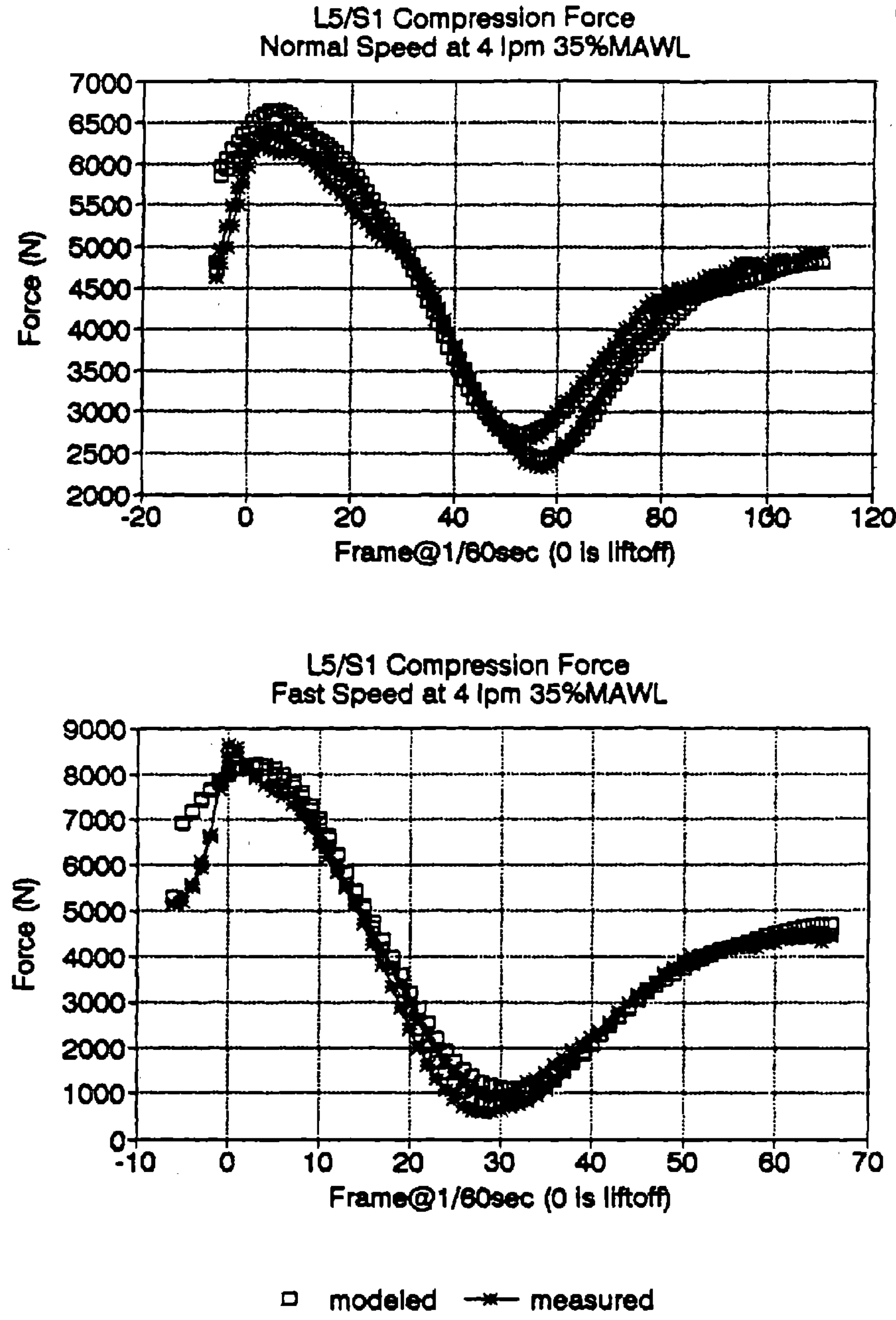
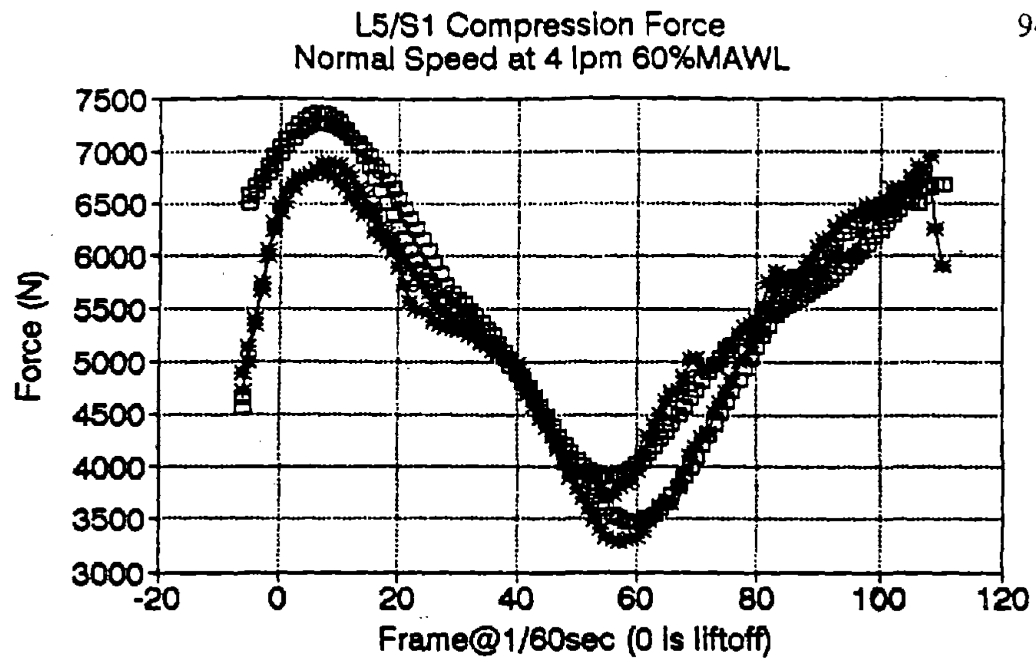


Figure 34. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 4 lpm and 35%MAWL performed at normal (top) and fast (bottom) speeds.



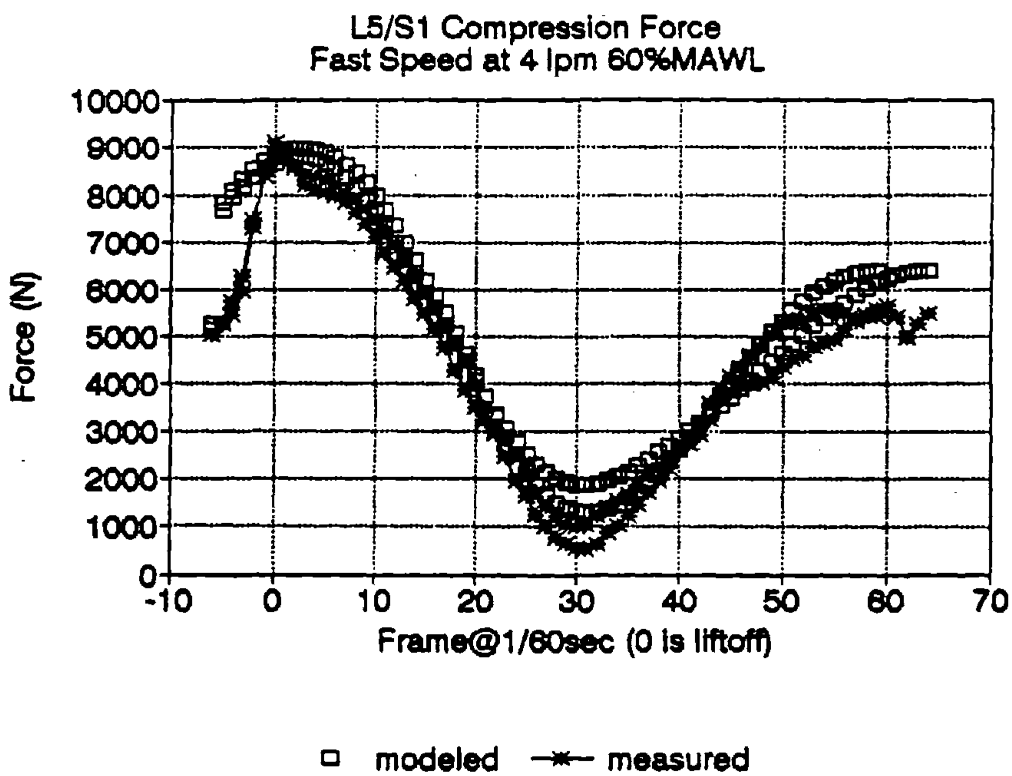


Figure 35. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 4 lpm and 60%MAWL performed at normal (top) and fast (bottom) speeds.

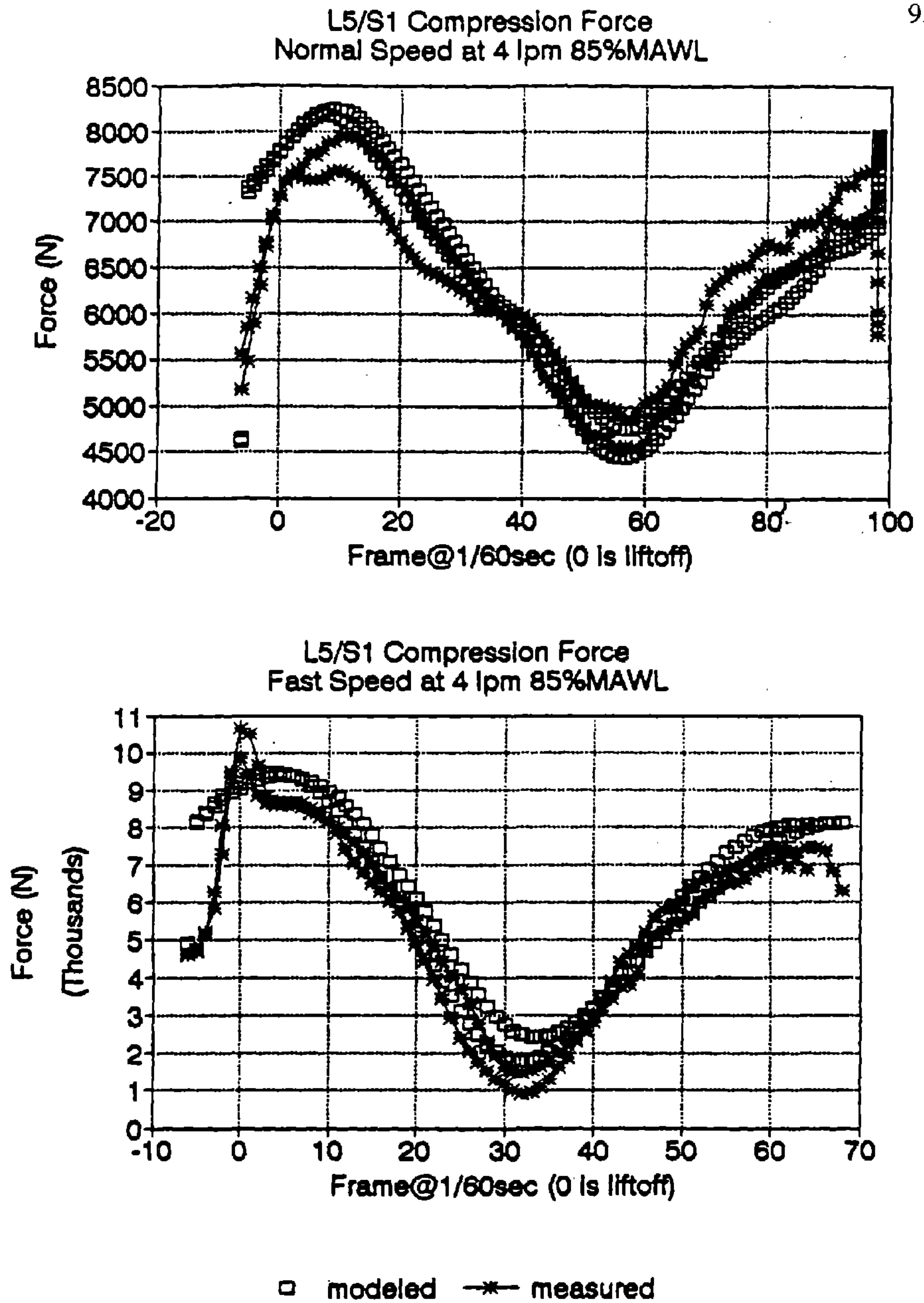


Figure 36. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 4 lpm and 85%MAWL performed at normal (top) and fast (bottom) speeds.

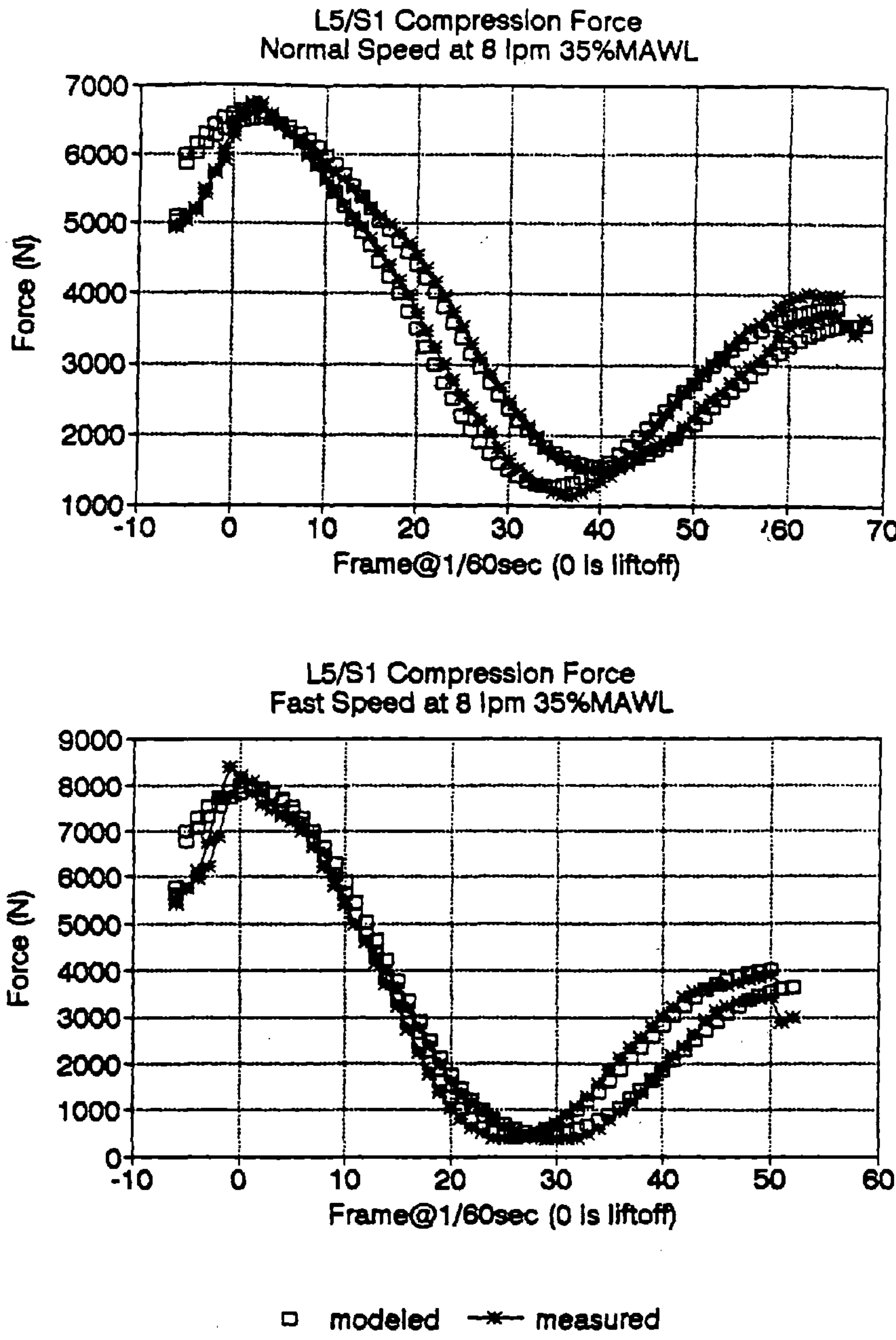


Figure 37. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 8 lpm and 35%MAWL performed at normal (top) and fast (bottom) speeds.

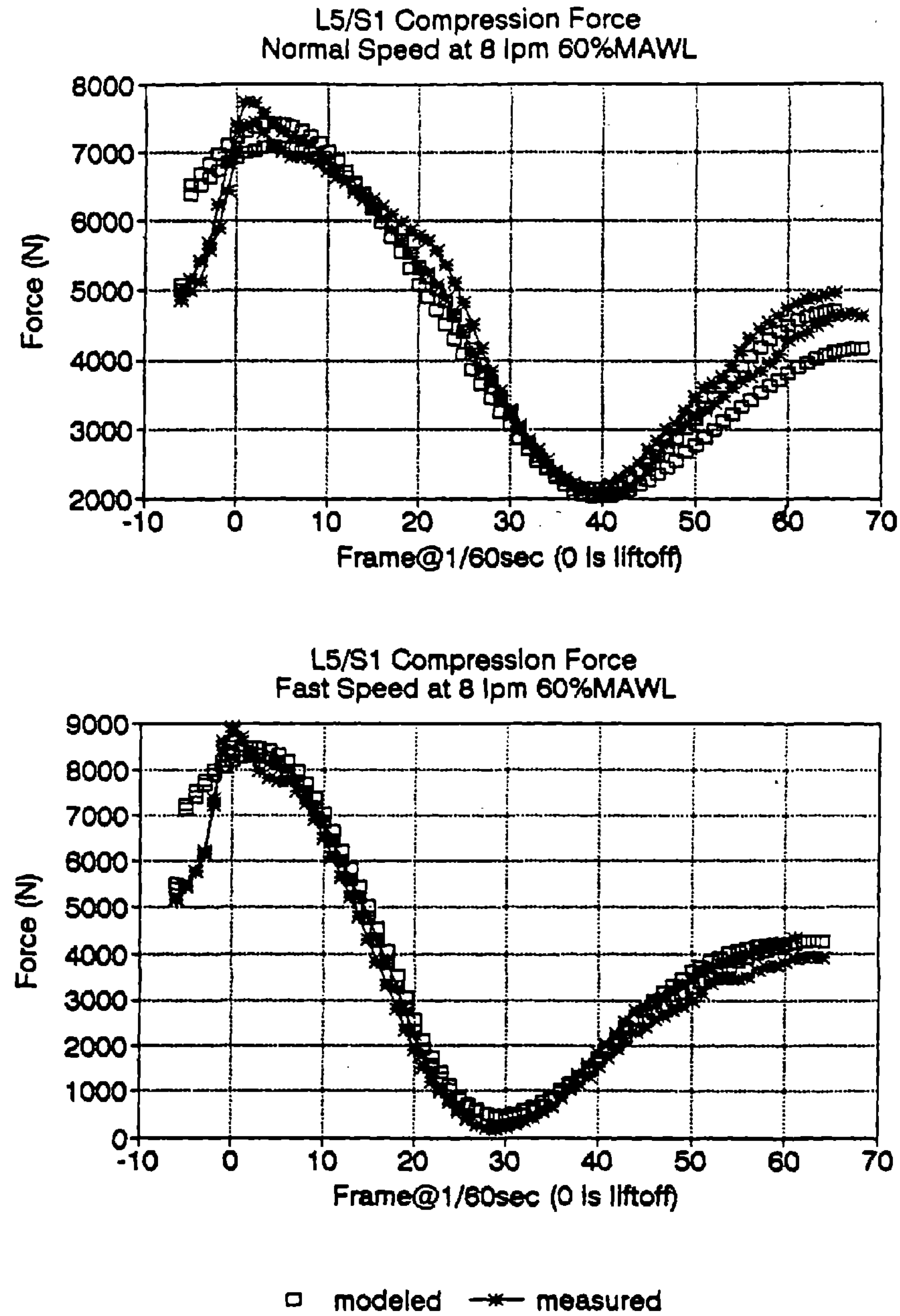


Figure 38. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 8 lpm and 60%MAWL performed at normal (top) and fast (bottom) speeds.

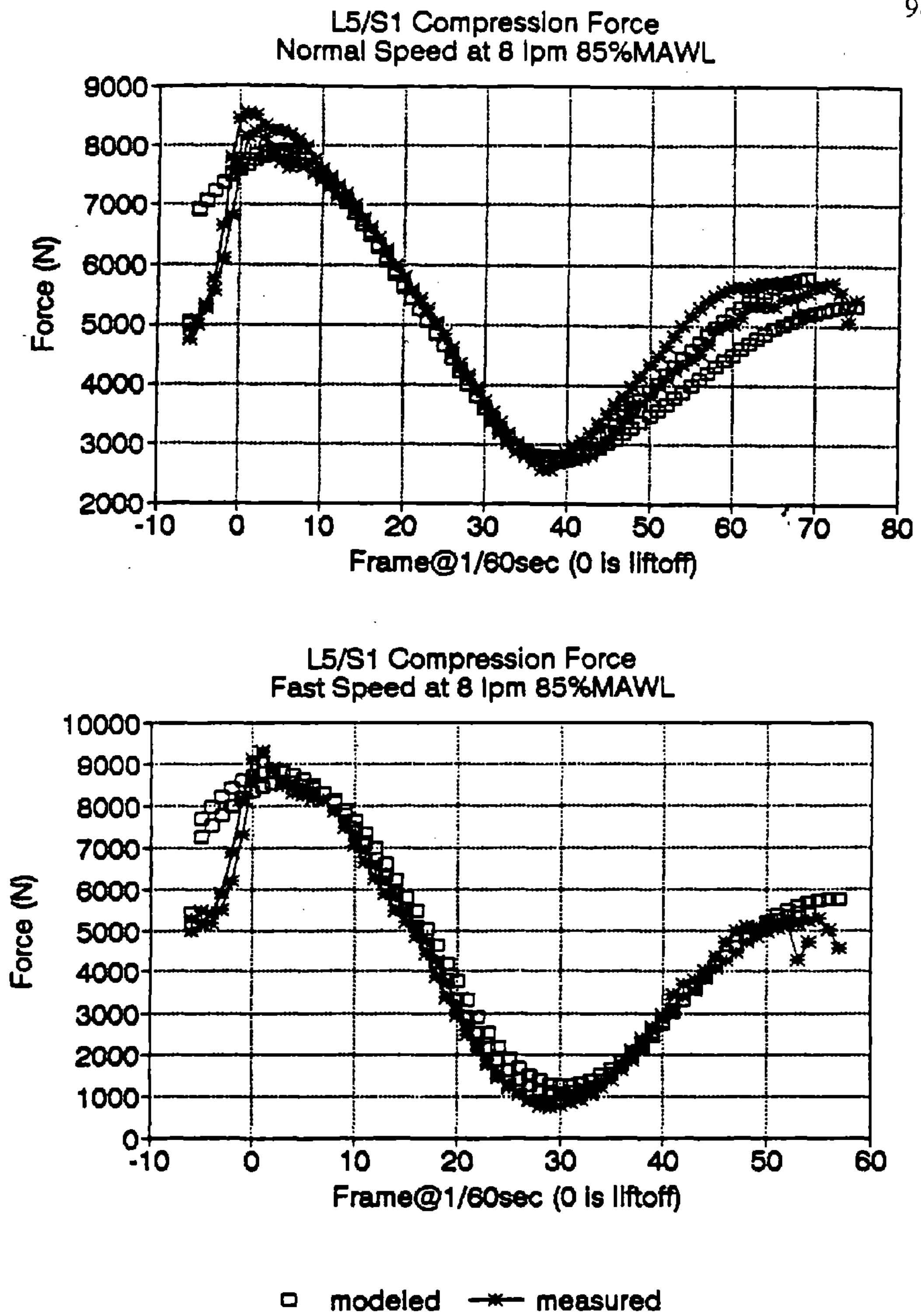


Figure 39. Plot of L5/S1 compression force calculated with the measured and modeled hand forces for two trials of 8 lpm and 85%MAWL performed at normal (top) and fast (bottom) speeds.

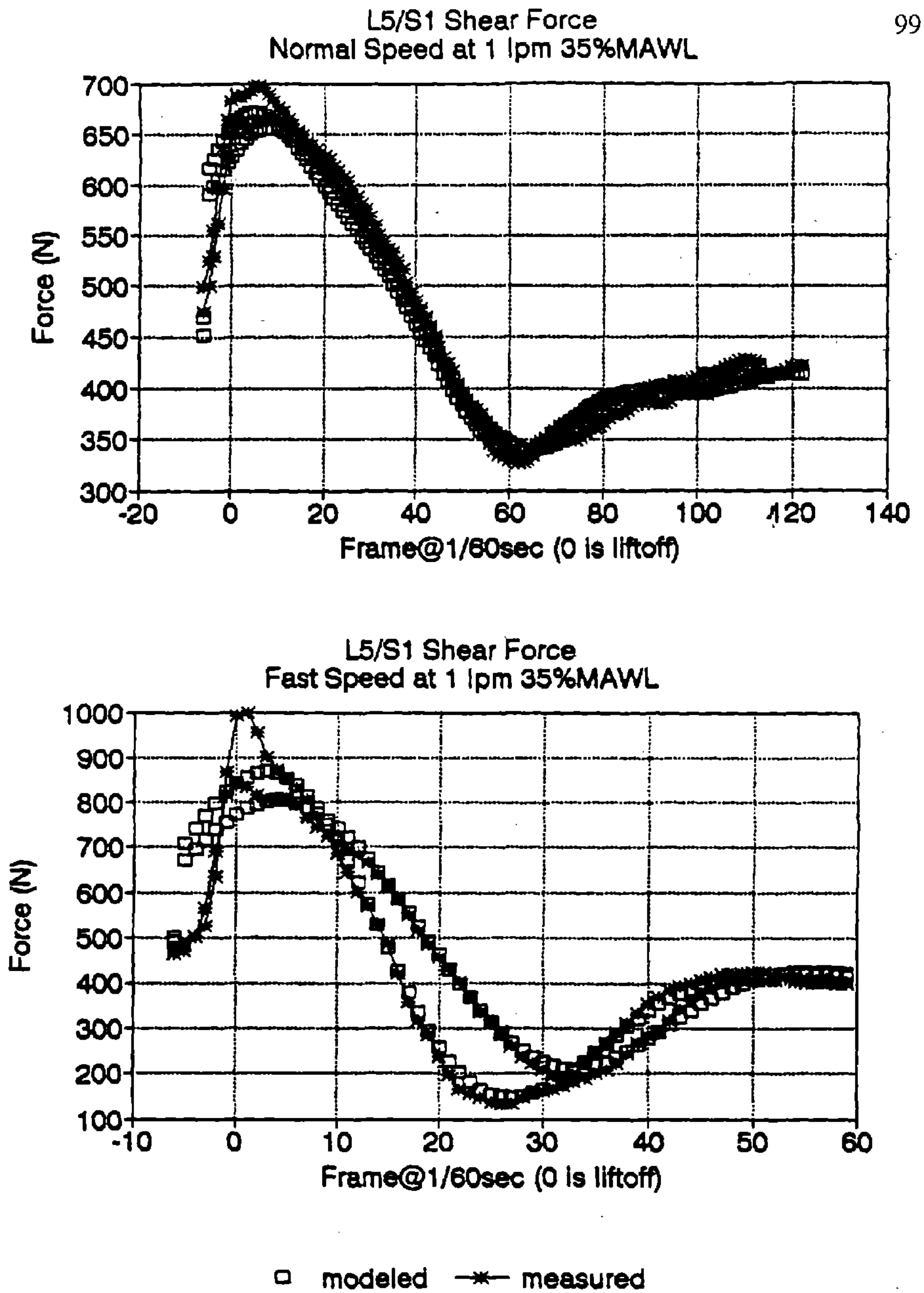


Figure 40. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 1 lpm and 35%MAWL performed at normal (top) and fast (bottom) speeds.

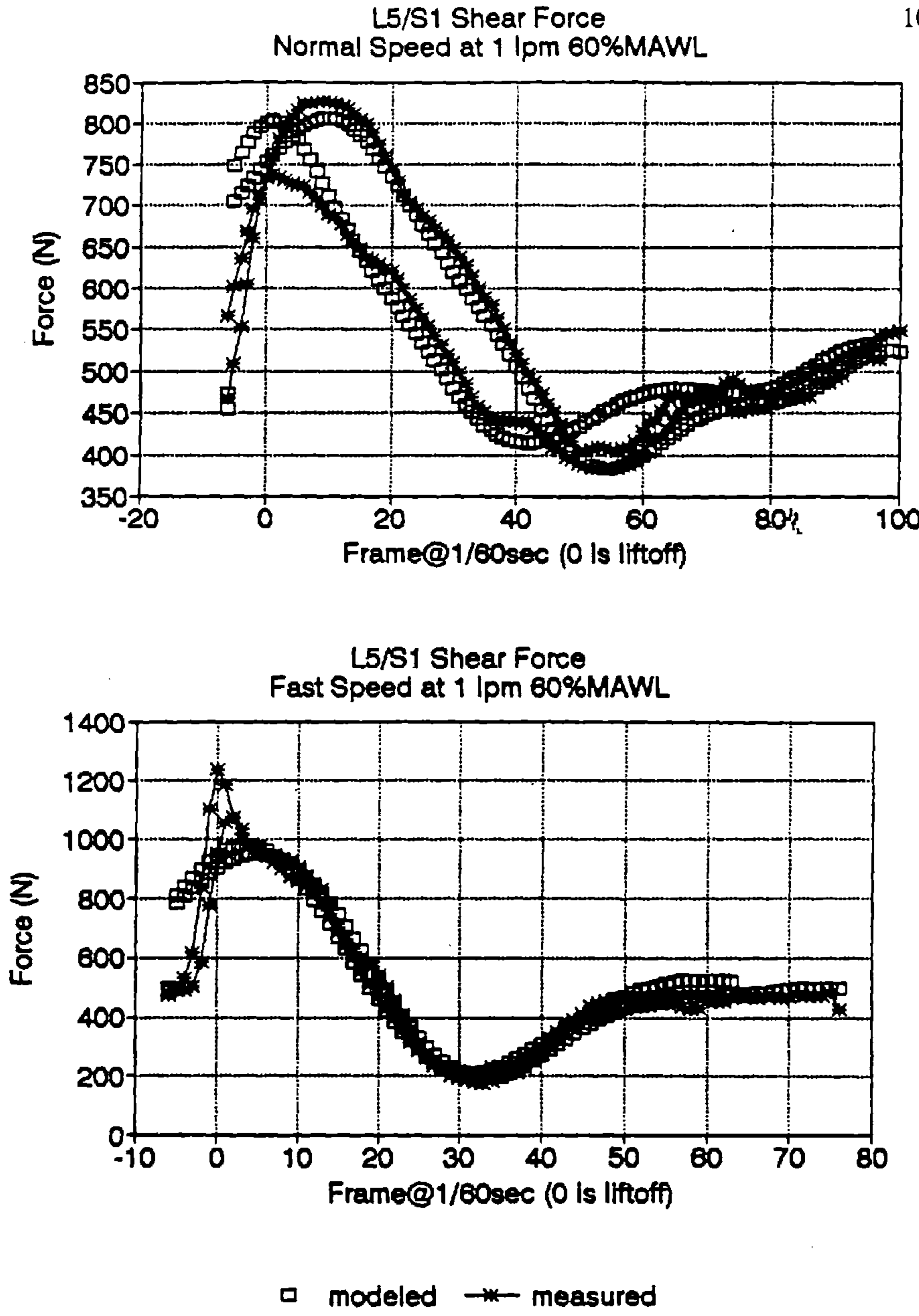


Figure 41. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 1 lpm and 60%MAWL performed at normal (top) and fast (bottom) speeds.

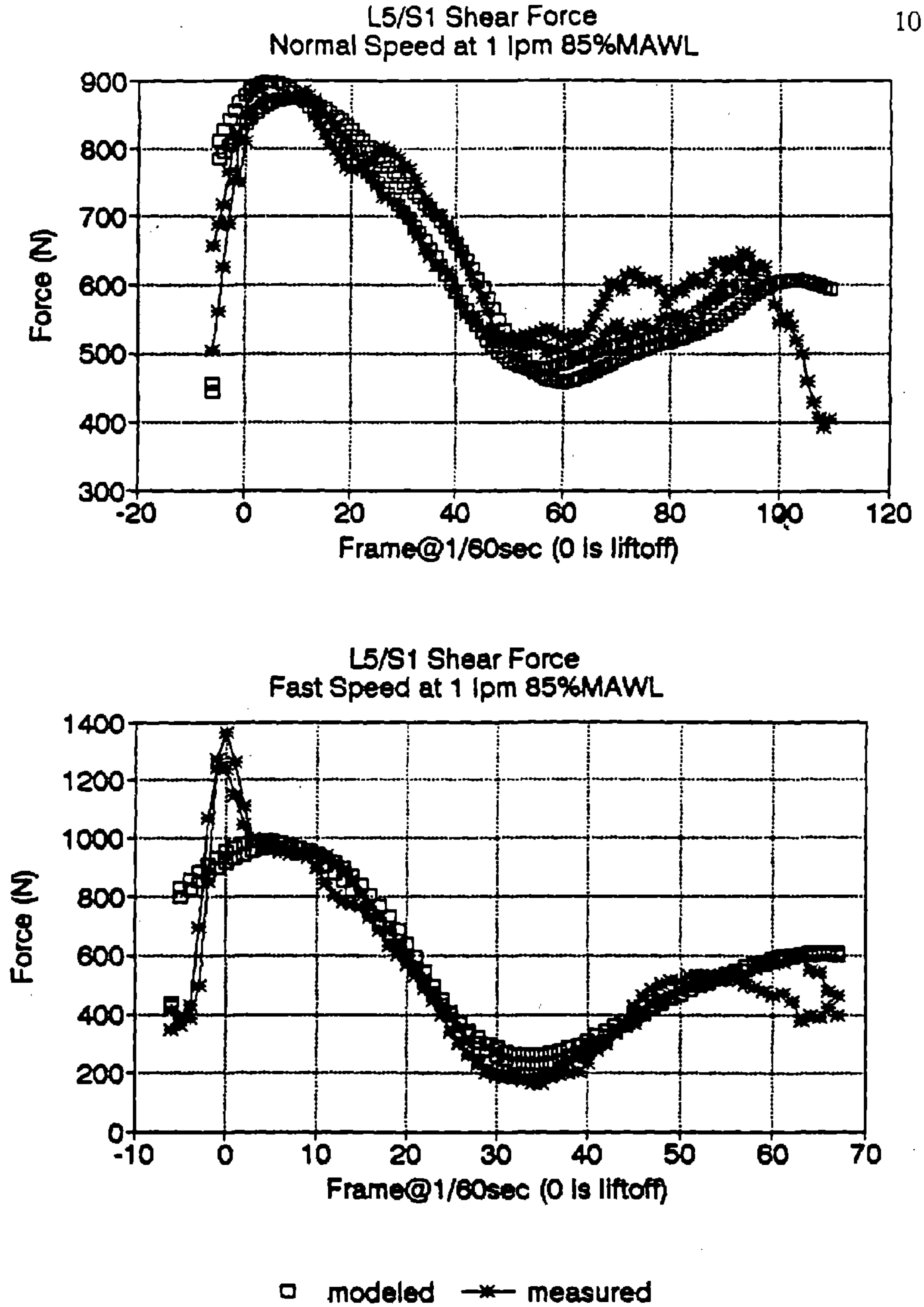


Figure 42. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 1 lpm and 85%MAWL performed at normal (top) and fast (bottom) speeds.

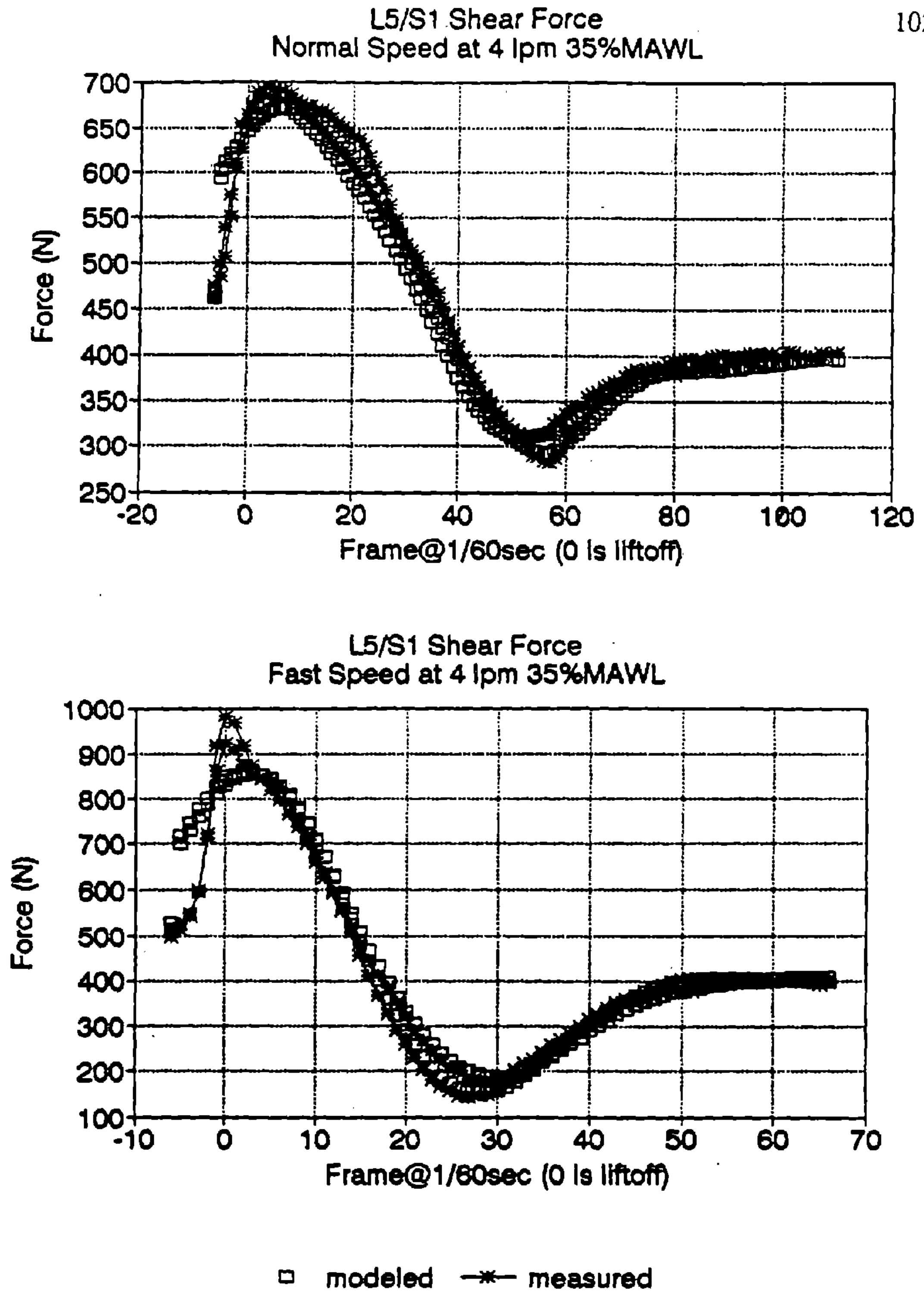


Figure 43. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 4 lpm and 35%MAWL performed at normal (top) and fast (bottom) speeds.

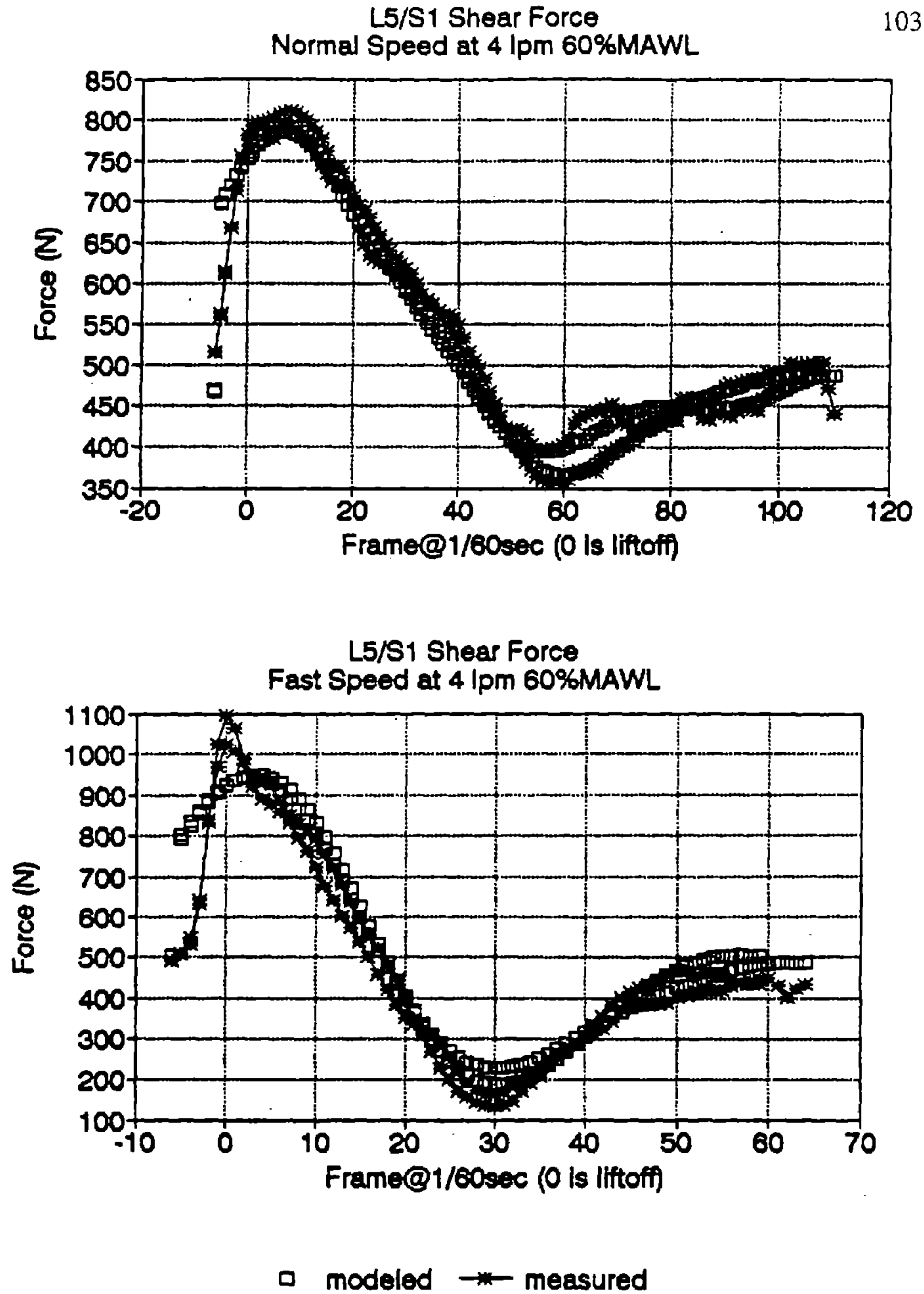


Figure 44. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 4 lpm and 60%MAWL performed at normal (top) and fast (bottom) speeds.

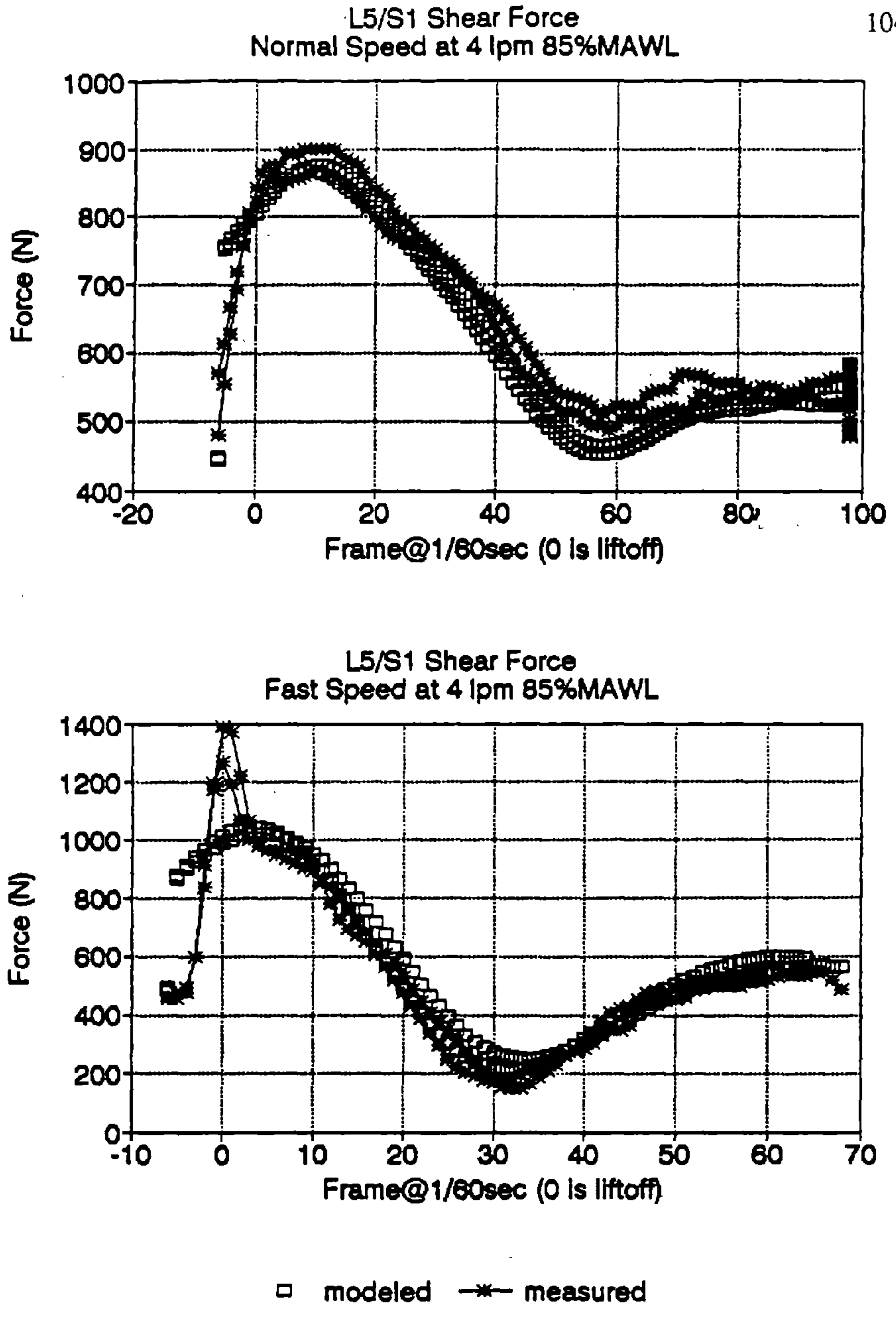


Figure 45. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 4 lpm and 85%MAWL performed at normal (top) and fast (bottom) speeds.

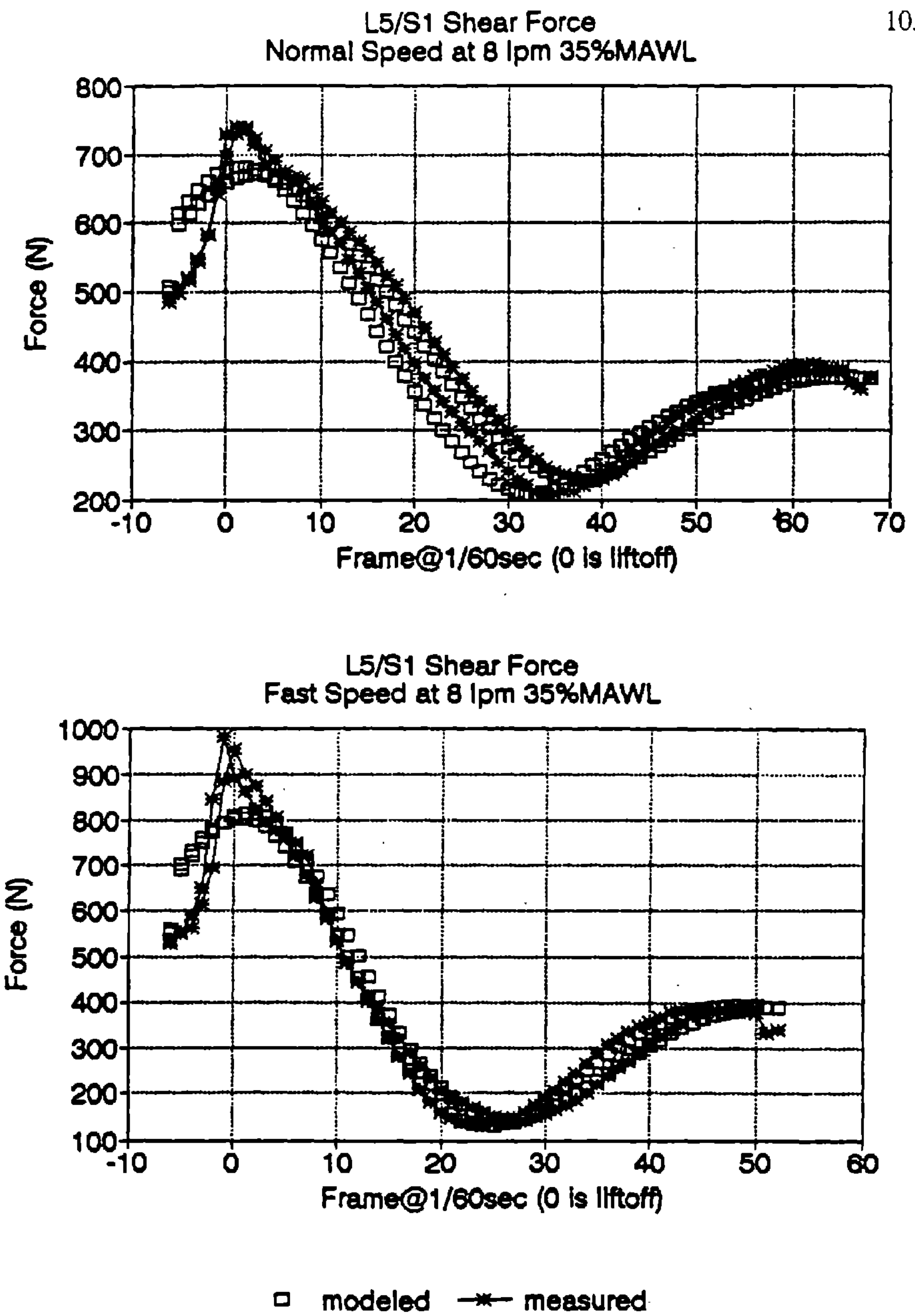


Figure 46. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 8 lpm and 35%MAWL performed at normal (top) and fast (bottom) speeds.

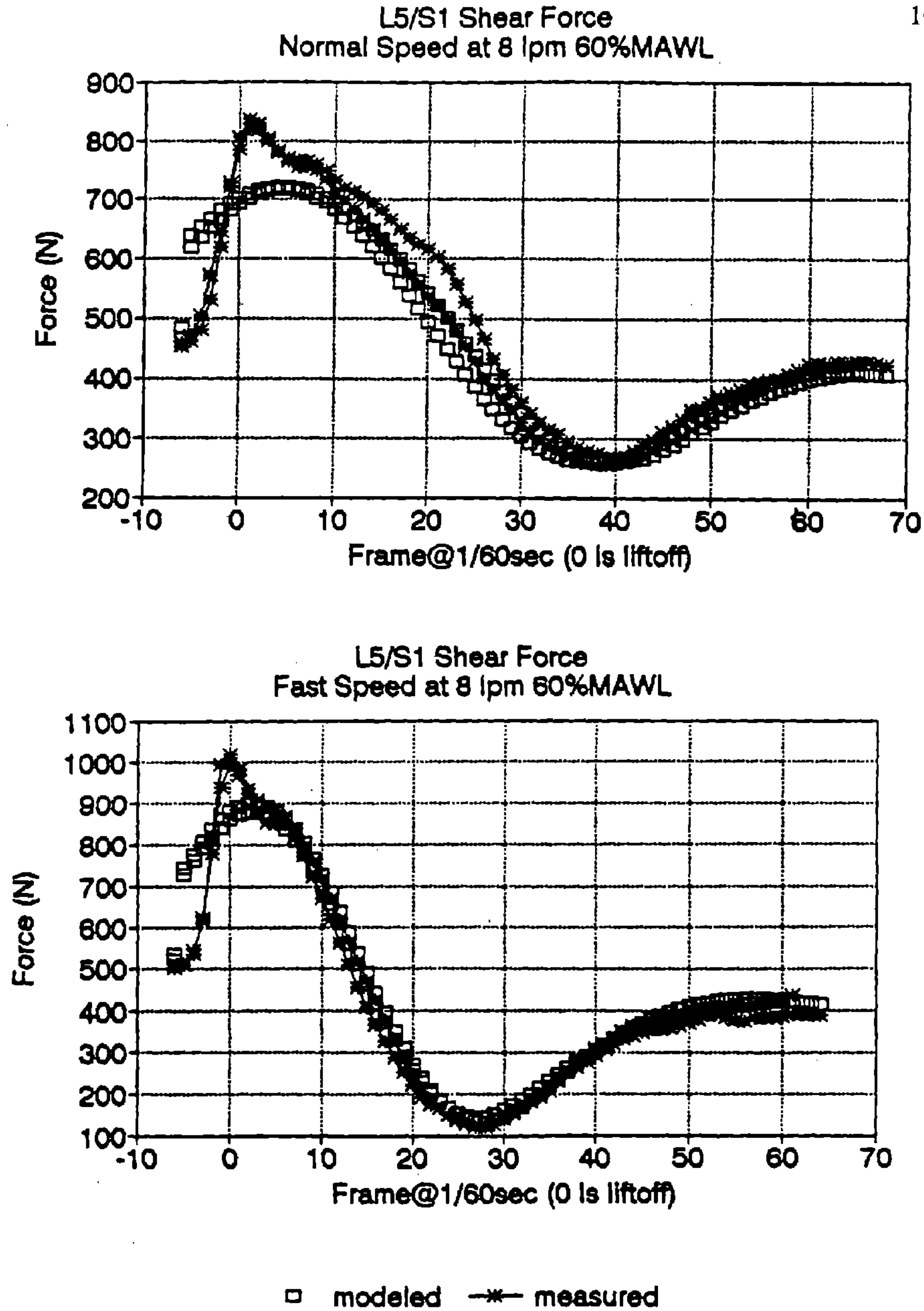


Figure 47. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 8 lpm and 60%MAWL performed at normal (top) and fast (bottom) speeds.

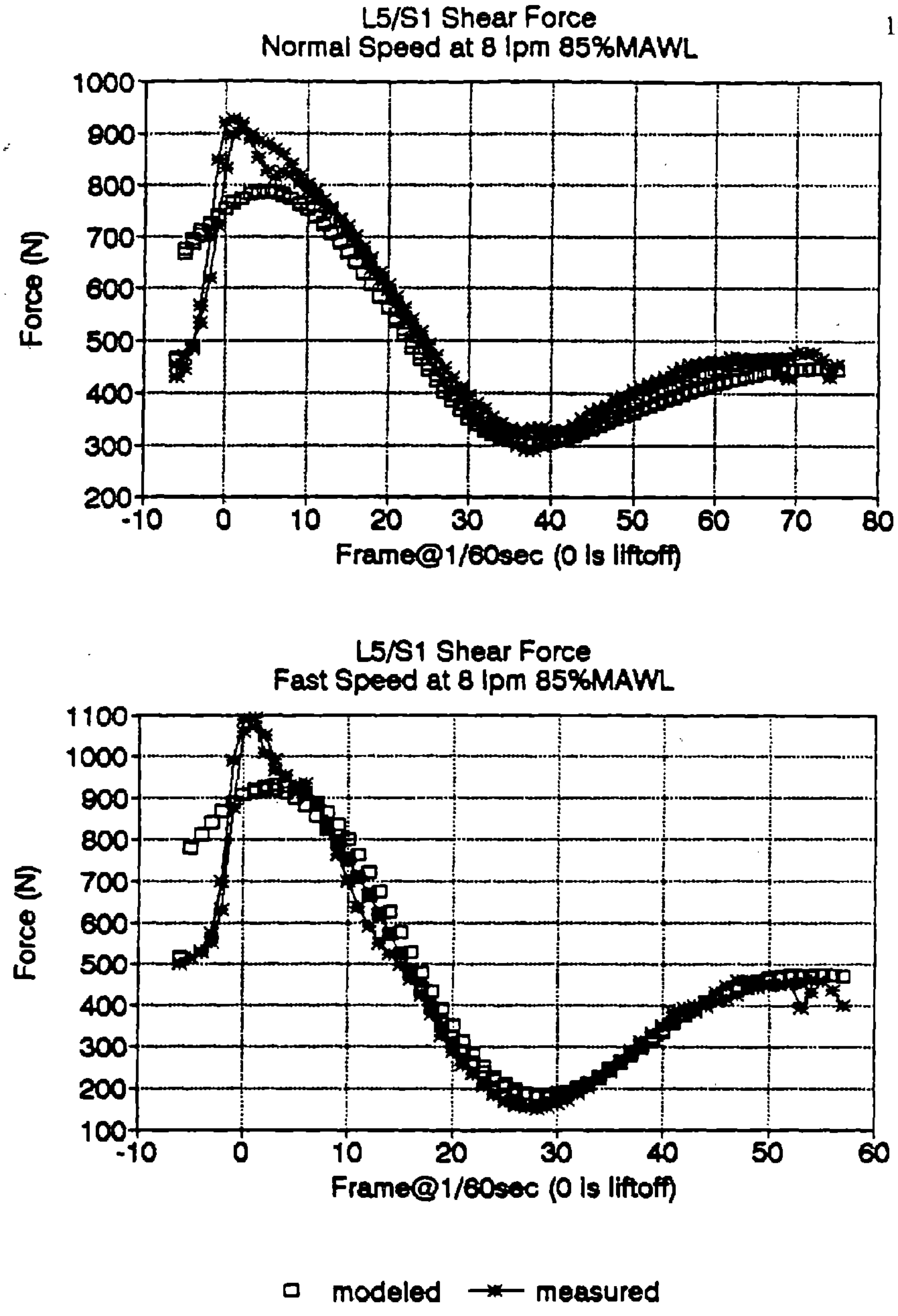


Figure 48. Plot of L5/S1 shear force calculated with the measured and modeled hand forces for two trials of 8 lpm and 85%MAWL performed at normal (top) and fast (bottom) speeds.

calculated with the measured and modeled hand forces for two trials of each of the nine lifting tasks for a single subject performing at normal and fast speeds. In general peak forces during the pull phase at L5/S1 were greater than modeled forces, but only forces at fast speeds of lift were significantly greater than the modeled forces. The L5/S1 forces are shown by two different curves. One curve (called the calculated curve) is the result of the L5/S1 compression and shear calculations of the biomechanical model using only video data and task variables as input. The other curve (called the measured curve) is the result of the L5/S1 compression and shear calculations of the biomechanical model using video data, task variables and measured forces at the hands as an additional input for reaction forces at the hands. Time series plots for fast lifts show that the L5/S1 compression peaked in a spike shape during the pull phase. These spikes usually exceeded the calculated curve, and in some cases then fell below the calculated curve. For fast lifting the spikes of the measured curve for L5/S1 compression ranged averages of 105 to 111% of the modeled curve over all frequencies and %MAWLs and as indicated in Table 16, these spikes were significantly greater than the peak modeled values.

For the time series plots of normal speed of lifting, the deviation of the L5/S1 compression measured curve from the calculated curve varies by frequency. During the pull phase, plots of the lower frequencies (1 and 4 lpm) show a hump, not a spike, and the hump does not exceed the calculated curve. For the highest frequency (8 lpm) at normal speed, the hump exceeds the calculated curve, but is still not classified as a spike. Overall the magnitude of these humps was not significantly greater than the peak magnitude of the modeled curve.

Plots of fast speeds of lift show spikes at all frequencies during the pull phase for L5/S1 shear force. For fast lifting the spikes of the measured curve for L5/S1 shear ranged from averages of 112 to 125% of the modeled curve, over all frequencies and %MAWLs, and as indicated in Table 16, these spikes were significant increases over the modeled curve.

For plots of normal speed of lifting, the deviation of the L5/S1 shear measured curve from the calculated curve also varies by frequency. The force plots of the lower frequencies (1 and 4 lpm) showed a hump, not a spike, which usually did not exceed the calculated value. The highest frequency (8 lpm) showed a spike for L5/S1 shear which was 110, 108 and 111% of the modeled value for 35, 60 and 85%MAWL, respectively.

Time of Peak Forces

Time of Peak Applied Forces by the Hands to the Load

The actual frame of liftoff did not consistently coincide with the peak measured vertical and horizontal peak forces applied by the hands to the container. Figures 49 through 52 illustrate a frequency count of the frames at which the peak vertical and horizontal forces occurred. The frequency charts are separated by lifting speeds: normal and fast. Zero is always when liftoff occurred as determined by the weight sensors in the platform. The bars with the shaded pattern represent the trials in which the vertical and horizontal forces were determined by calculations of the model. The bars with the black solid pattern represent the trials in which the vertical and horizontal forces were measured with the apparatus. As the charts show, the maximum vertical and horizontal forces applied by the hands to the load occurred in numerous trials before the load had left the ground, and up to four frames (4/60 sec) before liftoff.

Time of Peak Forces at L5/S1

Figures 53 through 56 illustrate a frequency count of the frames at which peak L5/S1 compression and shear forces occurred during the pull phase. The bars with the shaded

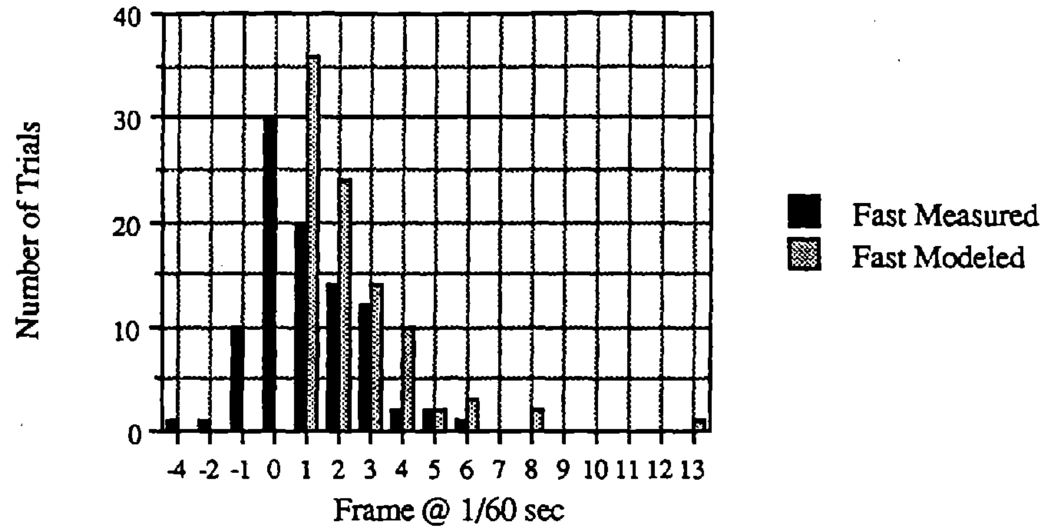


Figure 49. Occurrence of peak measured and modeled horizontal hand forces with respect to liftoff (frame zero) for fast lifting.

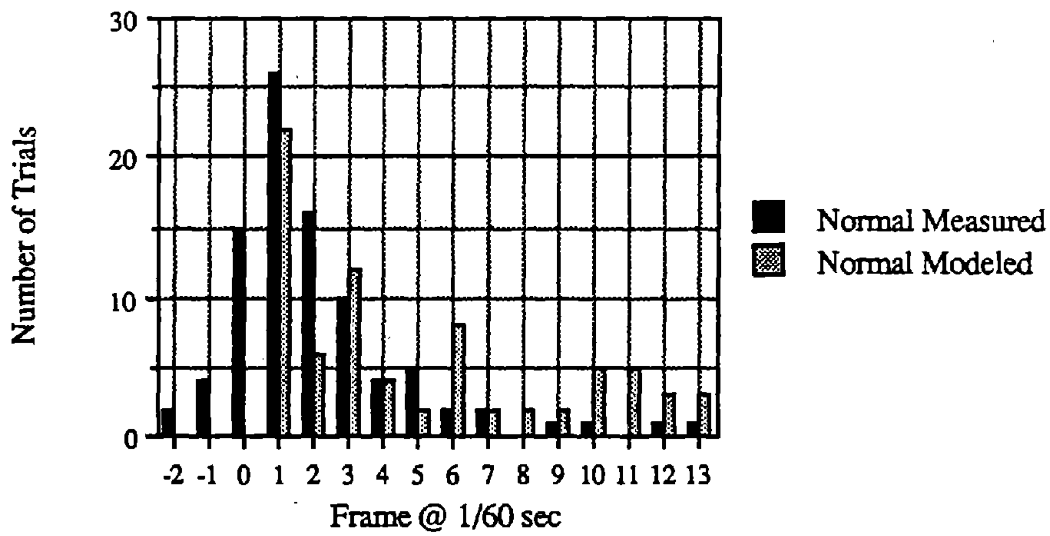


Figure 50. Occurrence of peak measured and modeled horizontal hand forces with respect to liftoff (frame zero) for normal lifting.

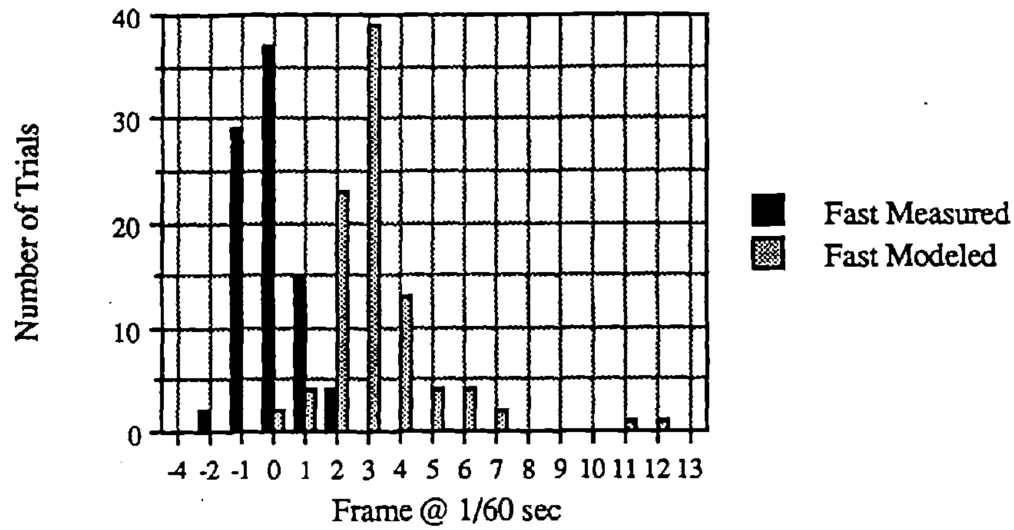


Figure 51. Occurrence of peak measured and modeled vertical hand forces with respect of liftoff (frame zero) for fast lifting.

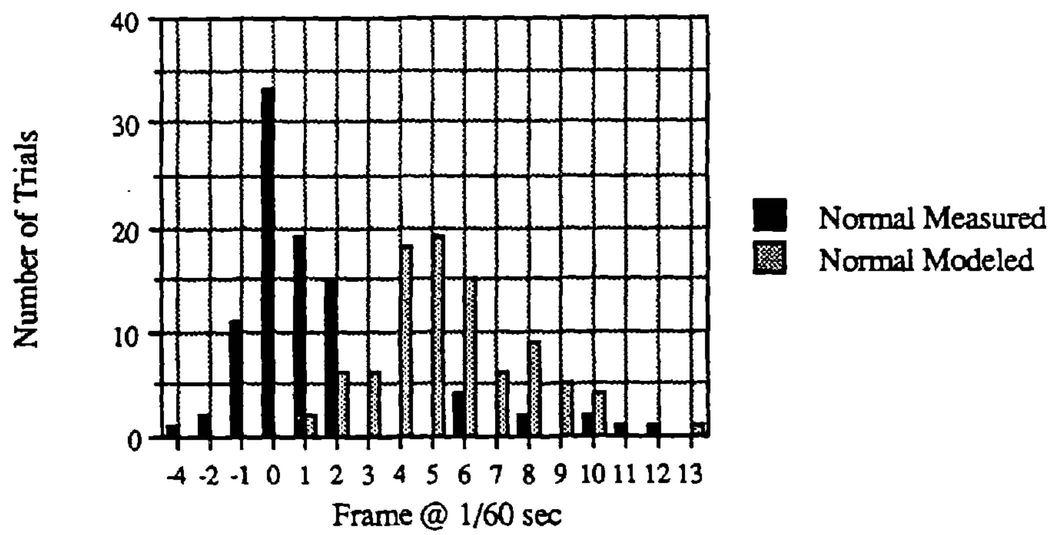


Figure 52. Occurrence of peak measured and modeled vertical hand forces with respect to liftoff (frame zero) for normal lifting.

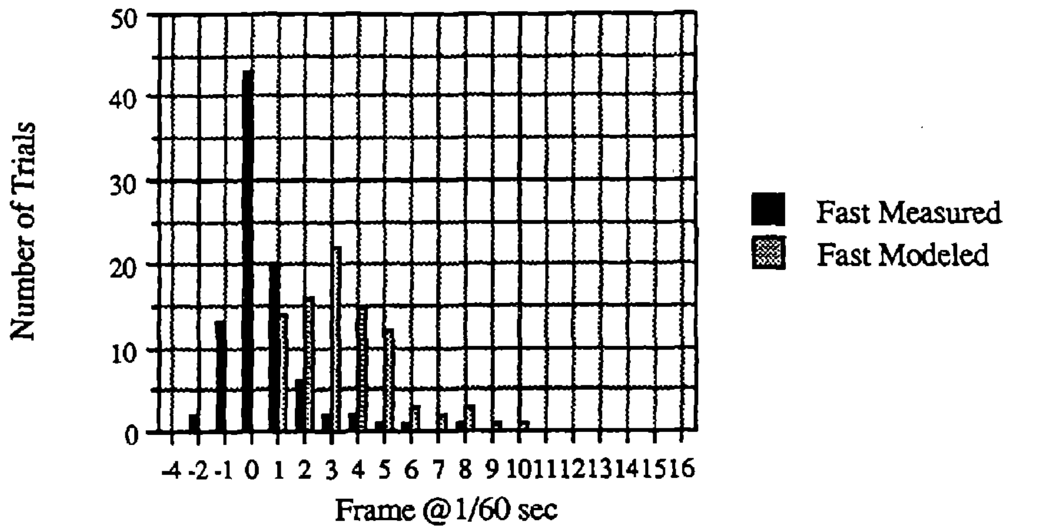


Figure 53. Occurrence of peak L5/S1 compression calculated with measured and modeled hand forces with respect to liftoff (frame zero) for fast lifting.

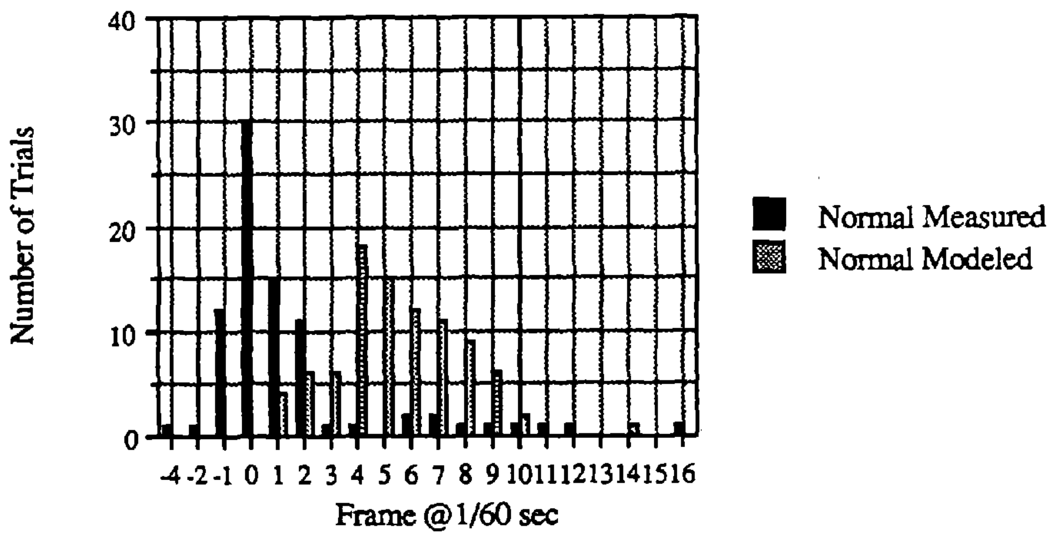


Figure 54. Occurrence of peak L5/S1 compression force calculated with measured and modeled hand forces with respect to liftoff (frame zero) for normal lifting.

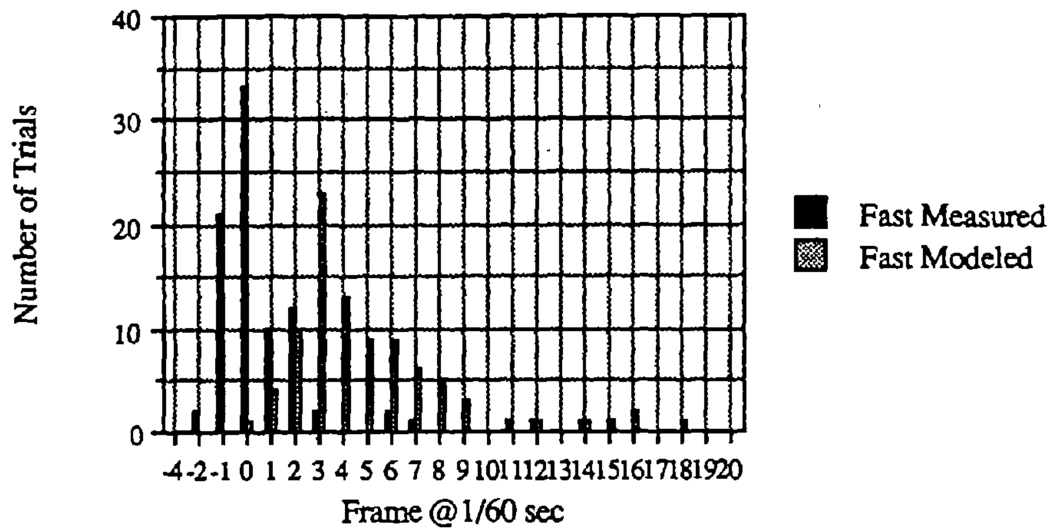


Figure 55. Occurrence of peak L5/S1 shear calculated with measured and modeled hand forces with respect to liftoff (time zero) for fast lifting.

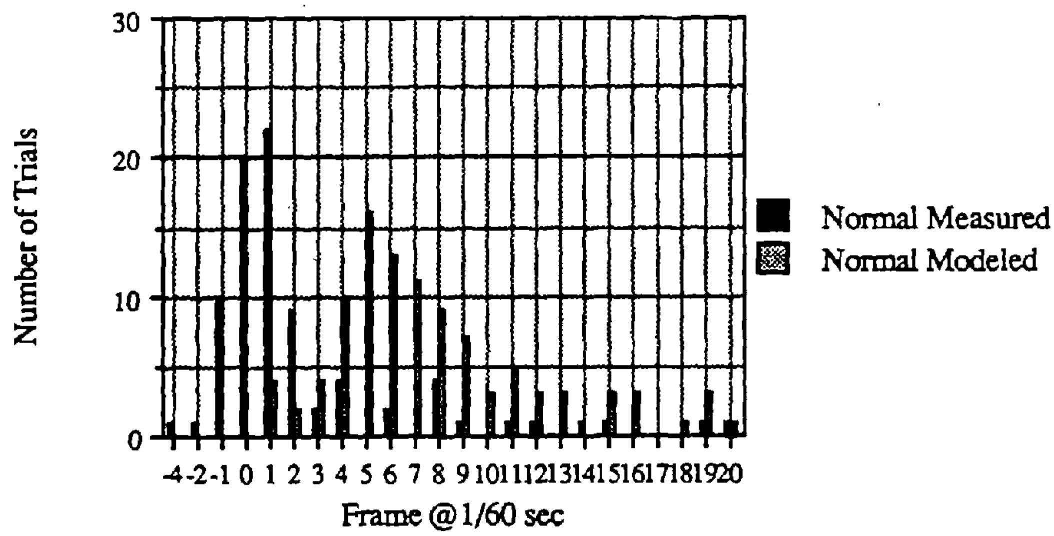


Figure 56. Occurrence of peak L5/S1 shear calculated with measured and modeled hand forces with respect to liftoff (frame zero) for normal lifting.

pattern represent the trials in which the L5/S1 forces were calculated using the model and the usual input data. The bars with the black solid pattern represent the trials in which the L5/S1 were calculated using the measured forces applied by the hands as direct input to the biomechanical model. As the charts show, the peak forces at L5/S1 occurred in several instances before the load had left the ground and up to four frames (4/60 sec) before liftoff.

Factors which Affect Measured Peak Applied Vertical Forces

Results from Experiment 1

Experiment 1 investigated the effects of %MAWL, frequency and lifting speed on peak forces applied by the hands and resulting peak forces at L5/S1. Specific effects of the variables and model summaries for vertical forces applied by the hands for Experiment 1 are shown in Table 17. Speed, frequency and %MAWL were highly significant main effects on peak vertical hand forces at significance levels (α's) of .0006, .0033 and .0001, respectively. The mean, standard deviation, minimum and maximum values are shown in Table 18 by speed, frequency and %MAWL. There were also two significant interactions: (1) speed and frequency at α of .0058 and (2) speed and %MAWL at α of .0190. Because of these significant interactions interpretation the main effects is complex. To aid in guiding interpretation of the data, Figures 57 through 60 are provided to illustrate the significant interactions on the vertical forces applied by the hands to the load. Table 19 summarizes the means and standard deviations for these figures.

To interpret the speed and frequency interaction, refer to Figures 57 and 58. Figure 57 shows that at fast lifting speeds the differences between the peak forces at the three frequencies become greater than at normal lifting speed. The average peak force while lifting fast at 8 lpm was 13 N less than the average peak force while lifting at normal speed at 1 lpm. This is especially interesting since on the average, the MAWL lifted at 1 lpm is twice the MAWL lifted at 8 lpm in this study. Figure 58 shows another perspective of this

Table 17. Model and significant effects summary for vertical forces applied by the hands to the load in Experiment 1.

Source	df	Sum of Squares	F Value	PR>F
Model	89	57985.39	36.12	0.0001
Error	90	1623.53		
Corrected Total	179	59608.91		
R Square	97%			
Speed	1	12805.34	93.68	.0006 *
Frequency	2	9812.34	12.67	.0033 *
%MAWL	2	18529.21	83.32	.0001 *
Speed*Frequency	2	1726.04	10.50	.0058 *
Speed*%MAWL	2	565.73	6.78	.0190 *

* $p \leq .05$

Table 18. Mean, standard deviation and range of the vertical peak applied forces (N) during the pull phase by speed, frequency, and %MAWL for Experiment 1.

Freq (lpm)	MAWL (%)	Lifting Speed Normal Mean	S.D.	Min	Max	Fast Mean	S.D.	Min	Max
	35	212	60	152	343	362	82	262	475
1	60	328	80	223	470	585	146	406	828
	85	418	128	276	635	727	203	489	1046
	35	156	25	122	183	287	68	198	372
4	60	252	42	177	293	444	144	297	753
	85	381	55	275	463	560	138	371	842
	35	129	29	85	180	204	60	137	315
8	60	216	51	145	303	294	63	217	393
	85	304	61	232	424	421	62	336	515

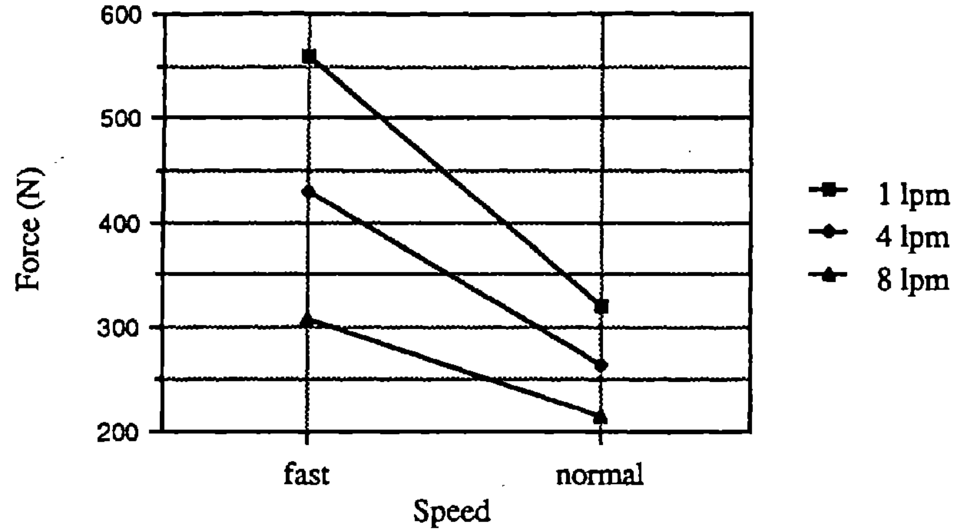


Figure 57. Speed and frequency interaction on measured vertical hand forces for normal and fast lifting.

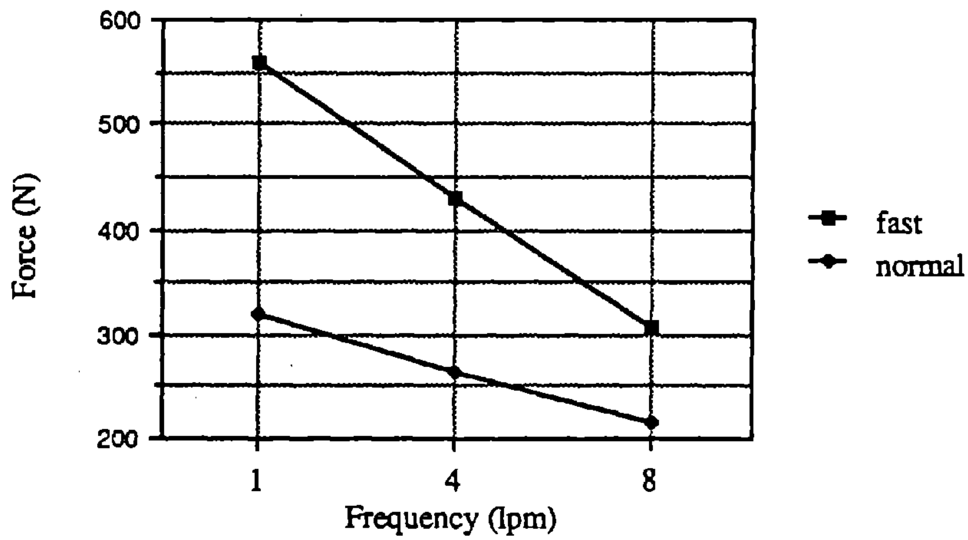


Figure 58. Frequency and speed interaction on measured vertical hand forces for normal and fast lifting.

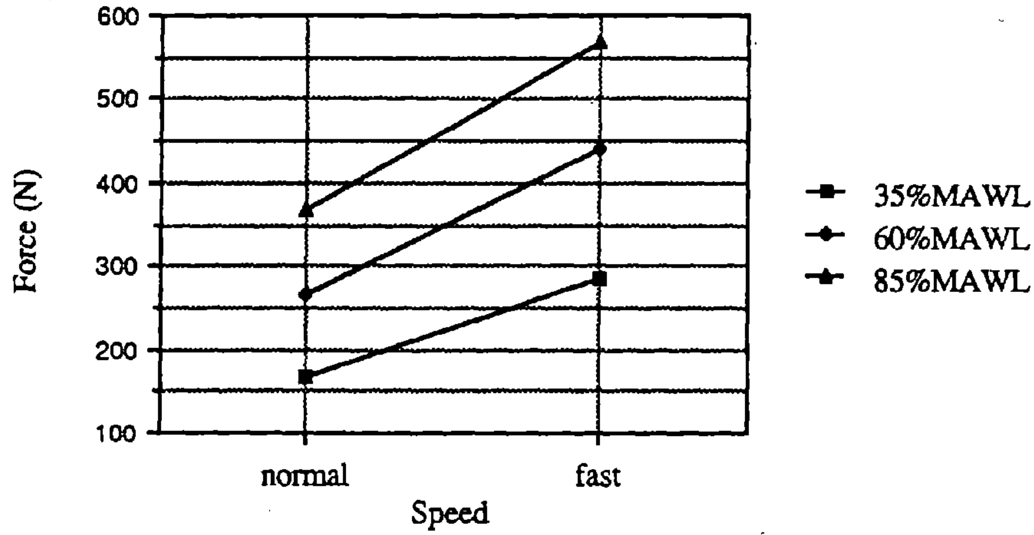


Figure 59. Speed and %MAWL interaction on measured vertical hand forces for normal and fast lifting.

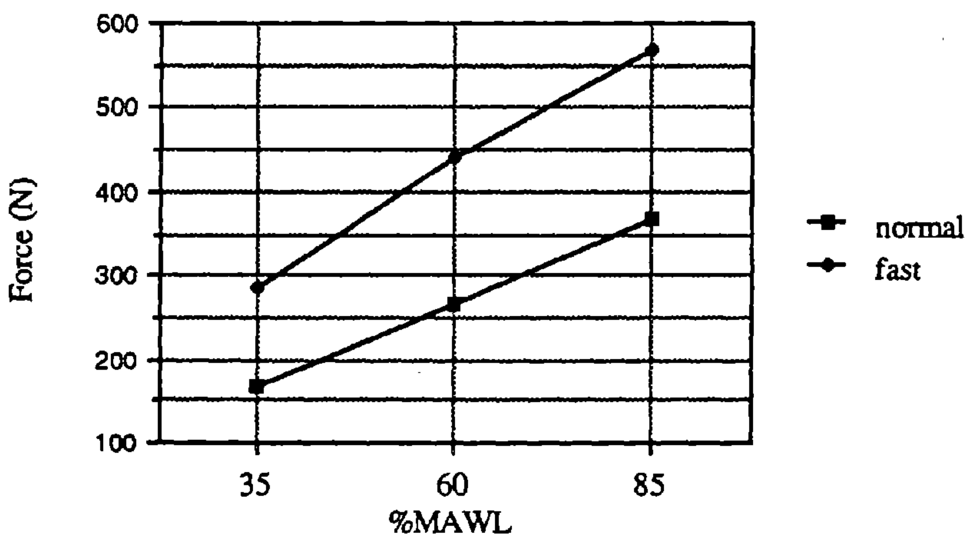


Figure 60. %MAWL and speed interaction on measured vertical hand forces for normal and fast lifting.

Table 19. Means and standard deviations for vertical hand forces (N) for Experiment 1.

Freq (lpm)	Normal	Fast	Change (N)	% Increase (Fast/Normal)*100
1	319 ± 125	558 ± 212	239	175
4	263± 102	430 ± 163	167	164
8	216± 86	306 ± 108	90	142
			Mean % Increase	160

speed and frequency interaction. From this point of view it is evident that the differences between the peak vertical hand forces at normal and fast speeds decrease as lifting frequency increases. This may be because the time to complete a normal lift becomes increasingly closer to the time to complete a fast lift as the frequency increases to 8 lpm and less time is available between lifts. In fact, this is the case as shown in the statistical analysis on time to complete the lift.

To examine the speed and %MAWL interaction effect refer to Figures 59 and 60. Figures 59 and 60 illustrate that the difference between the peak vertical forces during the fast and normal lifting speeds increase as the %MAWL increases. The peak vertical force which occurs when a load of 60% MAWL is lifted at normal speed is comparable to the peak vertical force from a 35% MAWL load lifted at fast speed.

Results from Experiment 2

Experiment 2 investigated the effects of weight and lifting speed on the peak hand forces on the load and the resulting L5/S1 forces while lifting at 1 lpm. Specific effects of the variables and model summaries for vertical forces applied by the hands for Experiment 2 are shown in Table 20. Speed and load were significant main effects on vertical forces at α's of .0313 and .0001, respectively. Interaction of speed and load was not significant. Figures 61 and 62 are provided to illustrate the main effects of speed and load on the vertical forces applied by the hands to the load.

Figure 62 shows that differences in peak vertical hand forces between the normal and fast lifting speeds increased as the load increased incrementally from 6.25 to 24.77 kg. However, in terms of percentage of increase, the increases at fast speed were between 156 to 178% of normal speed. For the lightest load of 6.25 kg the peak vertical hand force was 12.44 ± 2.68 kg for normal speed and 22.4 ± 3.63 kg at fast speed. Fast speed of lifting was 178% that of normal speed. For the heaviest load of 24.77 kg the average peak

Table 20. Model and significant effects summary for vertical forces (N) applied by the hands to the load in Experiment 2.

Source	df	Sum of Squares	F Value	PR>F
Model	49	42882.82	26.43	0.0001
Error	50	1655.66		
Corrected Total	99	44538.48		
R Square	96%			
Speed	1	9914.18	10.58	.0313 *
Load	4	23927.91	138.49	.0001 *

* $p \leq .05$

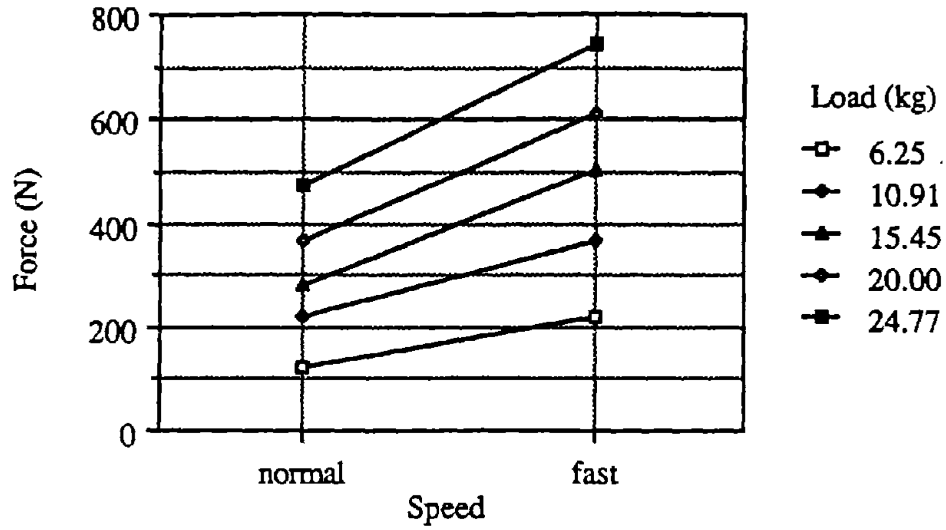


Figure 61. Speed and load interaction on measured vertical hand forces for normal and fast lifting.

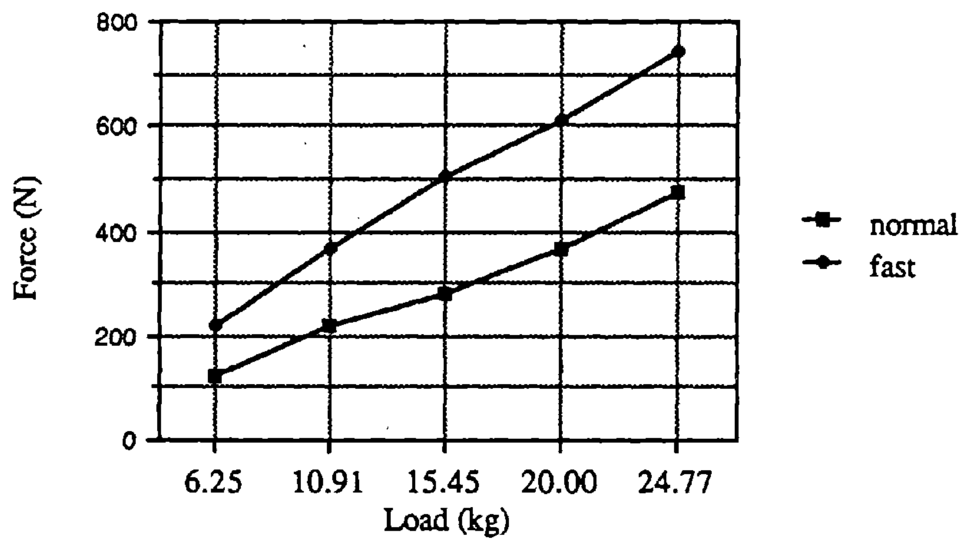


Figure 62. Load and speed interaction on measured vertical hand forces for normal and fast lifting.

vertical hand forces was 156% that of normal speed. Means for the vertical forces are plotted in Figures 61 and 62 and are summarized in Table 21 with standard deviations.

At normal speed, peak vertical hand forces applied to the load during the pull phase of a floor-to-knuckle height lift at 1 lpm ranged from 186 to 207% of the magnitude of the load. At fast speed, the peak vertical hand forces applied to the load ranged from 305 to 356% of the magnitude of the load.

Factors which Affect Measured Peak Horizontal Applied Forces

Results from Experiment 1

Specific effects of the variables and model summaries for peak horizontal hand forces applied to the load are shown in Table 22. Speed, frequency and %MAWL were significant main effects on horizontal force applied by the hands to the load with α's of .0042, .0056 and .0001, respectively. Table 23 lists mean, standard deviation, minimum and maximum values by speed, frequency and %MAWL. The speed and frequency interaction effect was not significant. To interpret the speed and frequency interaction effects on peak horizontal hand force, refer to Figures 63 and 64. The interaction is similar to that of speed and frequency effect on peak vertical force. Figure 63 shows that the differences in peak horizontal hand force between the normal and fast speeds increased as the lifting frequency became lower. The peak horizontal hand force for fast lifting at 8 lpm was 113% of the peak horizontal force at the normal speed of lift at 1 lpm. Again, this is interesting since the MAWL lifted at 1 lpm is on the average twice the MAWL lifted at 8 lpm. Figure 64 also shows that the differences of peak horizontal force between normal and fast speeds of lift become smaller with increasing frequency of lift. Means and standard deviations for the horizontal forces are plotted in Figures 63 and 64 summarized in Table 24.

Table 21. Means and standard deviations of peak vertical hand forces (N) for Experiment 2.

Load (kg)	Lifting Speed			
	Normal	Fast	Change (N)	% Increase (Fast/Normal)*100
6.25	122 ± 26	218± 36	96	178
10.91	221 ± 50	369 ± 87	148	166
15.45	281 ± 58	505 ± 121	224	180
20.00	369 ± 58	610 ± 154	241	165
24.77	474 ± 110	742 ± 183	267	156
			Mean % Increase	169

Table 22. Model and significant effects summary for horizontal forces applied by the hands to the load in Experiment 1.

Source	df	Sum of Squares	F Value	PR>F
Model	89	8642.64	20.99	0.0001
Error	90	416.28		
Corrected Total	179	9058.92		
R Square	95%			
Speed	1	2175.14	34.46	.0042 *
Frequency	2	1056.40	10.62	.0056 *
%MAWL	2	1977.41	41.76	.0001 *
Speed*Frequency	2	218.24	3.55	.0789

* $p \leq .05$

Table 23. Mean, standard deviation and range of the horizontal peak applied forces (N) during the pull phase by speed, frequency, and %MAWL for Experiment 1. The negative sign indicates that direction of force originated at the load and was directed toward the lifter's body.

Freq (lpm)	MAWL (%)	Lifting Speed Normal Mean	S.D.	Min	Max	Fast Mean	S.D.	Min	Max
1	35	-56	21	-84	-25	-116	49	-198	-55
	60	-87	42	-136	-36	-203	75	-355	-108
	85	-140	83	-249	-34	-253	51	-311	-173
4	35	-44	22	-78	-22	-107	22	-138	-71
	60	-71	37	-130	-32	-128	54	-283	-51
	85	-104	59	-238	-40	-178	45	-226	-105
8	35	-39	24	-88	-10	-78	30	-131	-36
	60	-58	31	-106	-18	-96	21	-132	-68
	85	-93	24	-137	-61	-148	44	-244	-95

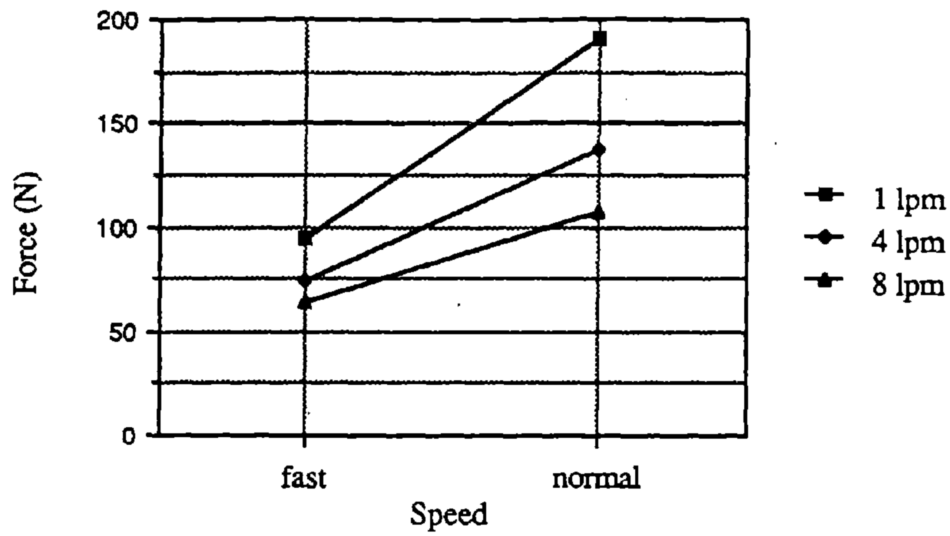


Figure 63. Speed and frequency interaction on measured horizontal hand forces for normal and fast lifting.

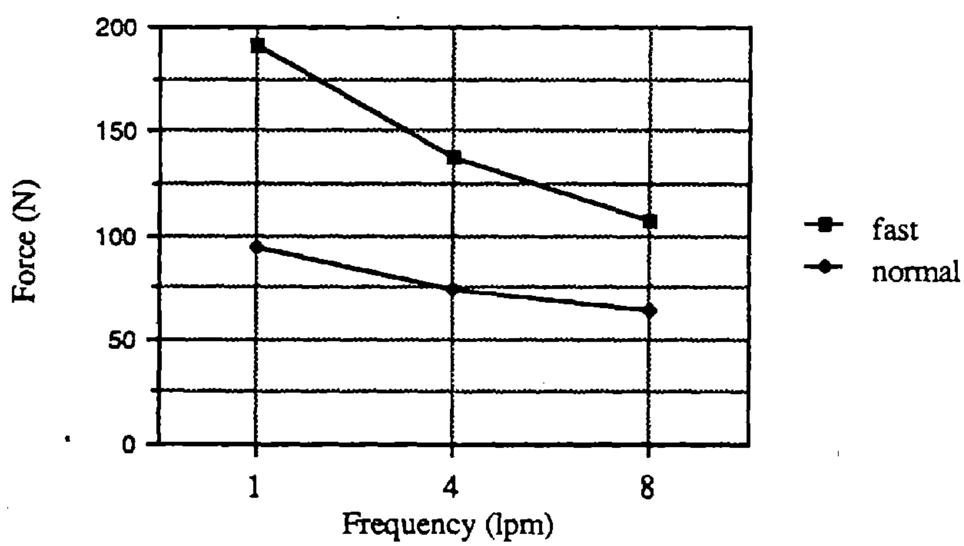


Figure 64. Frequency and speed interaction on measured horizontal hand forces for normal and fast lifting.

Table 24. Means and standard deviations of measured peak horizontal hand forces for Experiment 1. The negative sign indicates that direction of force originated at the load and was directed toward the lifter's body.

Frequency (lpm)	Lifting Speed			
	Normal	Fast	Change (N)	% Increase (Fast/Normal)*100
1	-95 ±64	-191 ± 81	96	202
4	-73± 48	-138 ± 51	64	188
8	-63 ± 34	-107 ± 44	44	169
			Mean % Increase	186

Results from Experiment 2

Experiment 2 investigated the effects of weight and lifting speed on the peak horizontal hand forces while lifting at 1 lpm. Specific effects of the variables and the model summaries for peak horizontal hand forces for Experiment 2 are shown in Table 25. Speed and load were significant main effects on horizontal force applied by the hands to the load with significance levels of .0101 and .0001, respectively. The speed and frequency interaction effect was not significant. The speed and load main effects on peak horizontal forces applied by the hands are plotted in Figures 65 and 66. Both figures show that the horizontal component of the peak applied force by the hands to the heaviest load (24.77 kg) for both normal and fast speeds of lift was proportionately greater than the trend of the other four incremental loads from 6.25 to 20.00 kg. Figures 65 and 66 also show that for increasing weight the differences between peak horizontal hand forces for normal and fast lifting speeds also increased.

At normal speed, peak horizontal hand forces applied during the pull phase of the floor-to-knuckle lift at 1 lpm ranged from 44 to 55% of the magnitude of the load. At fast speed the peak horizontal hand forces applied to the load ranged from 83 to 117% of the magnitude of the load. Means and standard deviations for the horizontal forces are plotted in Figures 65 and 66 and are summarized in Table 26.

A summary of resultant forces for horizontal and vertical hand forces as percent of load are shown in Table 27. Overall, for lifting at 1 lpm, resultant forces of the measured hand forces ranged from 190 to 210% of the magnitude of the load for normal speed lifting, and from 320 to 370% of the load for fast speed. Measured horizontal forces were about half of the magnitude of the load for normal speed of lift, ranging from 44 to 50% of the load with no apparent trend with respect to weight of load. Measured horizontal forces were about equal to the magnitude of the load for fast speed of lift, ranging from 83 to 117% of load with no apparent trend with respect to weight of load. Measured vertical

Table 25. Model and significant effects summary for horizontal forces (N) applied by the hands to the load in Experiment 2.

Source	df	Sum of Squares	F Value	PR>F
Model	49	4918.31	27.76	0.0001
Error	50	180.79		
Corrected Total	99	5099.11		
R Square	95%			
Speed	1	1394.72	21.12	.0101 *
Load	4	2161.95	34.55	.0001 *

* $p \leq .05$

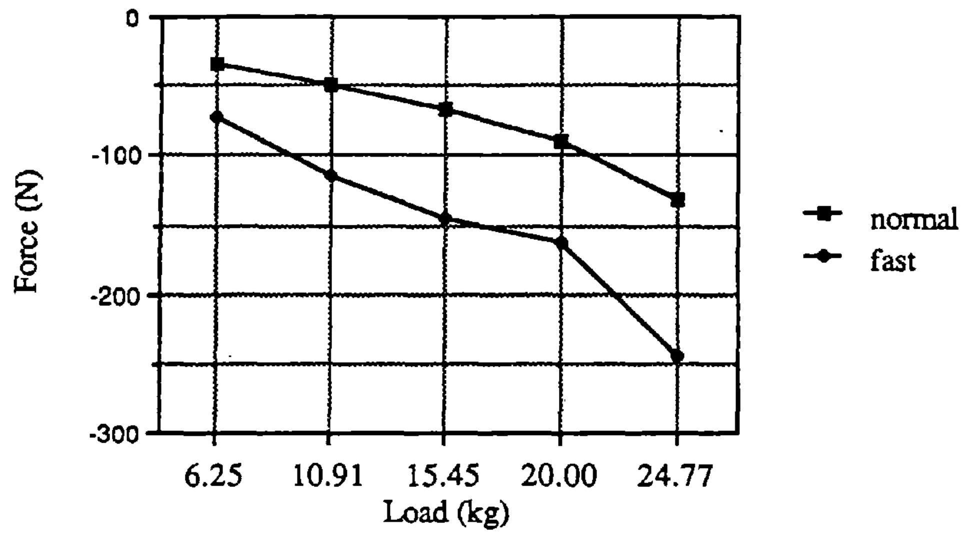


Figure 65. Load and speed interaction on measured horizontal hand forces for normal and fast lifting.

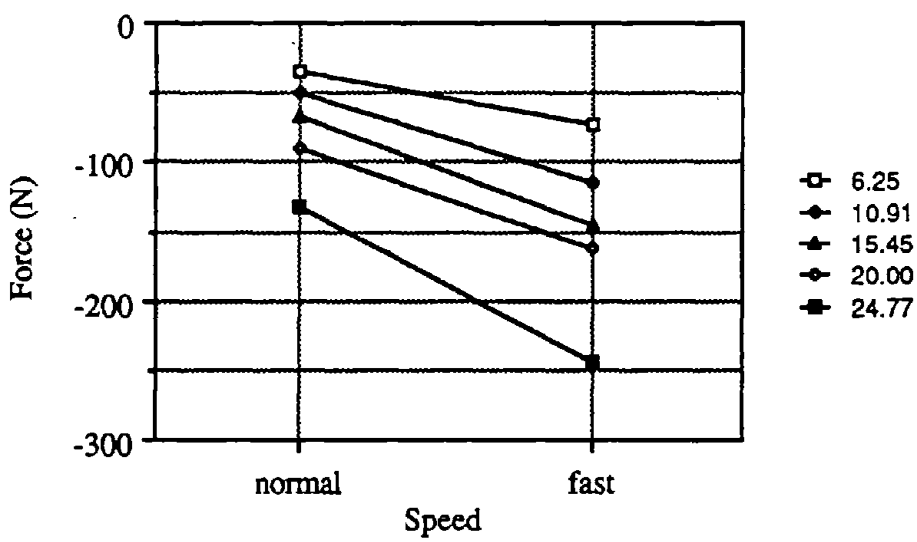


Figure 66. Speed and load interaction on measured horizontal hand forces for normal and fast lifting.

Table 26. Means and standard deviations for the horizontal forces for Experiment 2.

Load (kg)	Lifting Speed			
	Normal	Fast	Change (N)	% Increase (Fast/Normal)*100
6.25	34 ± 15	72 ± 19	38	211
10.91	50 ± 15	114 ± 26	65	229
15.45	67 ± 19	144 ± 129	78	216
20.00	90 ± 22	163 ± 57	73	181
24.77	131 ± 50	244 ± 76	113	186
			Mean % Increase	205

Table 27. Resultant forces of horizontal and vertical hand components and relationship to magnitude of load for normal and fast lifting at 1 lpm.

	Horizontal % of Load		Vertical % of Load		Resultant % of Load	
Load (kg)	Normal	Fast	Normal	Fast	Normal	Fast
6.25	55	117	201	370	206	375
10.91	47	107	210	320	212	345
15.45	44	95	190	350	191	347
20.00	46	83	190	320	194	322
24.77	54	101	200	320	203	322

forces were about twice the magnitude of the load for normal speed of lift, ranging from 188 to 207% of the load, and about three times the magnitude of the load for fast speed of lift, ranging from 305 to 356%. Again, there was no relationship with respect to weight of load. However, the contribution of the vertical component of the applied hand forces was three to four times that of the horizontal component, depending on the speed of lift. For normal speed lifting the contribution of vertical force was 3.7 to 4.5 times the peak horizontal force. However, for fast speed, the contribution of the horizontal component increased slightly, with the vertical forces ranging from 3.0 to 3.9 times that of the horizontal component.

Factors which Affect Peak Forces at the L5/S1 Calculated with Measured Input

Results from Experiment 1

It is of interest to know the magnitude of the compression and shear forces which occur during the pull phase since in this phase the limiting maximum force for the entire lift is often experienced by the lifter, and since the magnitudes of the measured peak hand forces were significantly greater than modeled. Experiment 1 investigated the effects of speed, frequency and %MAWL on measured peak applied forces and the resulting modeled forces at L5/S1. The model statement for L5/S1 shear in Experiment 1 is shown in Table 28, in which speed and frequency are significant main effects of .0273 and .0103, respectively. Figures 67 through 70 show the plots of %MAWL and frequency effects on L5/S1 shear and Table 29 lists the corresponding means. For Experiment 1, the magnitude of the shear force never exceeded 98 kg which is substantially below the tolerance limit of 1.735 kN (177 kg) recommended by Farfan et al. (1976). Table 30 lists the mean, standard deviation, and the range of the peak L5/S1 shear during the pull phase by speed, frequency and %MAWL as determined in Experiment 1 using the measured hand forces.

Table 28. Model and significant effects summary for L5/S1 shear in Experiment 1.

Source	df	Sum of Squares	F Value	PR>F
Model	89	106152.74	44.24	0.0001
Error	90	2426.26		
Corrected Total	179	108579.00		
R Square	95%			
Speed	1	15435.68	11.41	.0278 *
Frequency	2	3199.53	8.57	.0103 *
%MAWL	2	15810.76	4.90	.0408 *

* $p \leq .05$

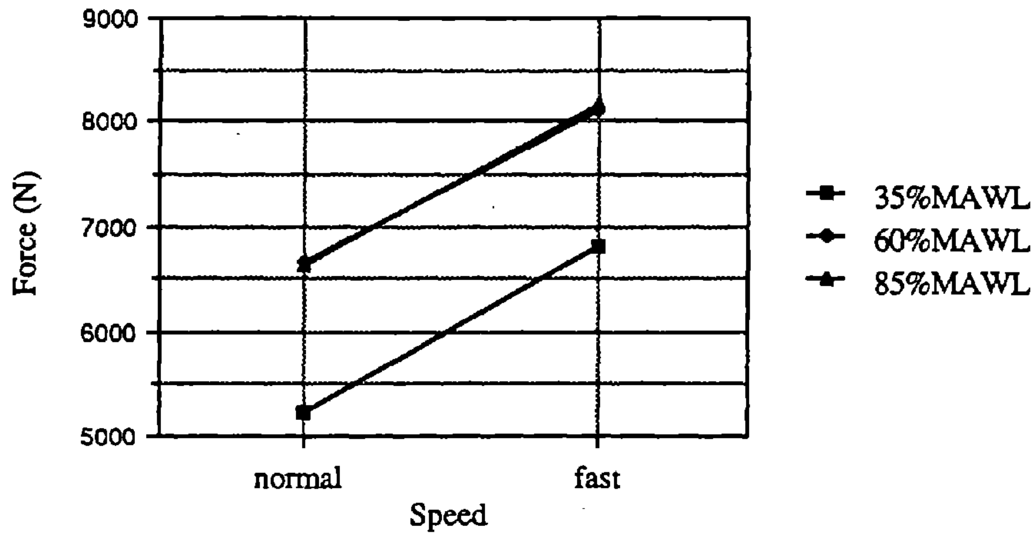


Figure 67. Speed and %MAWL interaction on L5/S1 compression forces calculated with measured hand forces for normal and fast lifting.

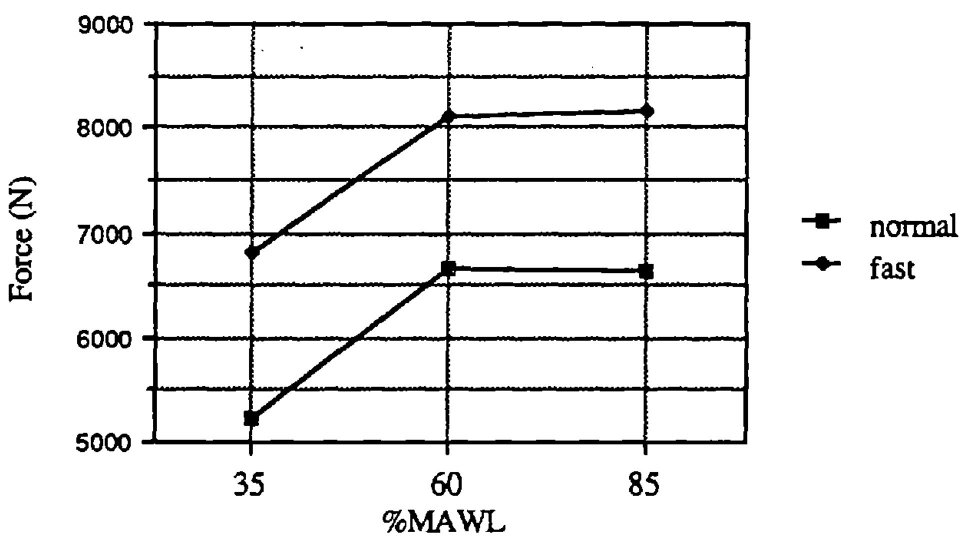


Figure 68. %MAWL and speed interaction on L5/S1 compression forces calculated with measured hand forces for normal and fast lifting.

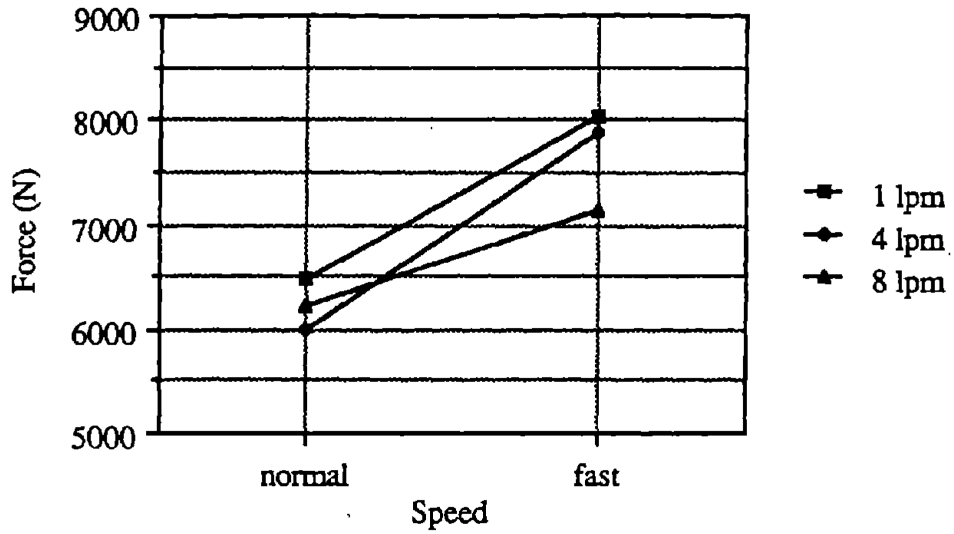


Figure 69. Speed and frequency interaction on L5/S1 compression forces calculated with measured hand forces for normal and fast lifting.

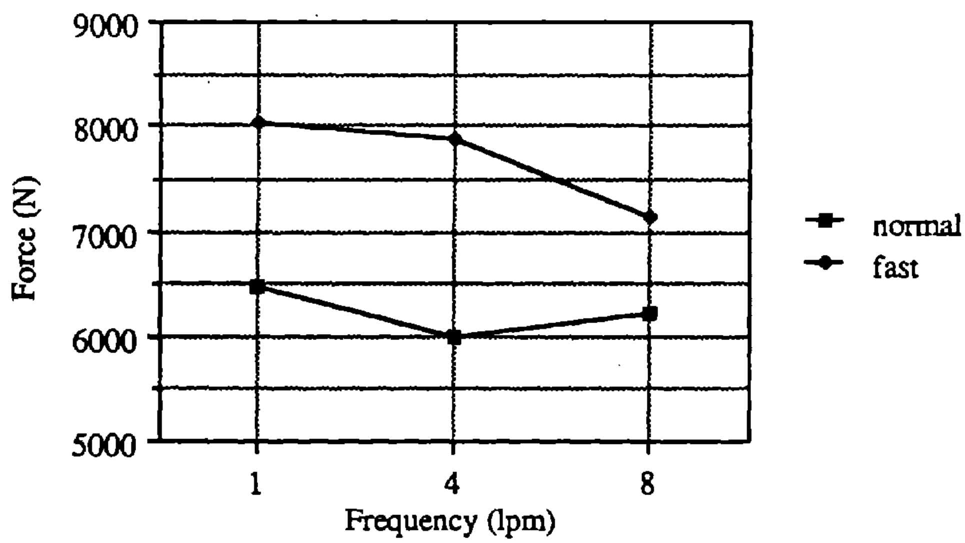


Figure 70. Frequency and speed interaction on L5/S1 compression forces calculated with measured hand forces for normal and fast lifting.

Table 29. Means and standard deviations of L5/S1 shear by frequency, %MAWL and speed for Experiment 1.

	Lifting Speed		
	Normal	Fast	% Increase (Fast/Normal)*100
Frequency (lpm)			
1	703± 201	888 ± 296	126
4	625 ± 177	883 ± 235	141
8	644 ± 159	746 ± 224	116
Load (%MAWL)			
35	542 ± 137	695 ± 239	128
60	716 ± 169	890 ± 178	124
85	714 ± 180	931 ± 294	130
		Mean % Increase	128

Table 30. Mean, standard deviation, and range of peak L5/S1 shear forces (N) by speed, frequency, and %MAWL for Experiment 1.

Freq (lpm)	MAWL (%)	Lifting Speed Normal Mean	S.D.	Min	Max	Fast Mean	S.D.	Min	Max
	35	567	154	313	774	731	271	348	11
1	60	808	200	574	1227	964	144	754	1186
	85	734	181	394	945	968	384	191	1366
	35	526	141	294	695	708	234	300	982
4	60	662	116	503	812	939	158	613	1128
	85	687	227	251	921	1003	217	721	1393
	35	532	126	388	741	648	226	362	983
8	60	678	156	435	853	766	175	556	1020
	85	722	138	593	927	823	251	387	1095

Unlike the shear forces, most of the lifts performed in this experiment are classified as risky for injury based on the compression for the L5/S1 joint according to the average tolerance limit of the spine 4.36 ± 1.88 kN (445 kg ± 192 kg) (Jager and Luttman, 1989) and the NIOSH (1981) recommendation of a maximum lift exposure of 6.4 kN (650 kg). Specific effects of the variables and model summary for compression force at L5/S1 for Experiment 1 are shown in Table 31. As shown in the model statement in Table 31, speed was the significant main effect at .0131 for L5/S1 compression. As shown in Table 32, fast lifting increased compression force on L5/S1 by an average of 24%, ranging from 15 to 31% depending on lifting frequency and %MAWL. Table 33 lists the mean, standard deviation, and range of the peak L5/S1 compression during the pull phase by speed, frequency and %MAWL as determined in Experiment 1 using the measured hand forces. Lifting tasks which resulted in average compression forces classified as dangerous based on the above specifications were lifts at 60 and 85%MAWL at 1, 4 and 8 lpm of normal lifting and all lifting conditions of fast lifting speed.

Results from Experiment 2

The model statement listed in Table 34 for L5/S1 compression indicates that speed and load were significant main effects of .0131 and .0001, respectively. Plots of speed and load for L5/S1 compression are shown in Figures 71 and 72. Corresponding means and standard deviations for these plots are shown in Table 35. Figures 71 and 72 illustrate the general trend that fast lifting speed increased L5/S1 peak compression forces by an average of 30%. Average L5/S1 peak compression forces of the lightest load of 6.25 kg lifted at a fast speed produced only an average of 400N less force on the spine than the heaviest load (24.77 kg) and 156N more than the 20.00 kg load.

Most of the lifts performed at 1 lpm in this experiment resulted in compression forces at L5/S1 classified as risky according to the average tolerance limit of the spine 4.36 ± 1.88

Table 31. Model and significant effects summary for L5/S1 compression in Experiment 1.

Source	df	Sum of Squares	F Value	PR>F
Model	89	4128250.64	44.97	0.0001
Error	90	92837.45		
Corrected Total	179	4221088.09		
R Square	98%			
Speed	1	996654.98	18.14	.0131 *
%MAWL	2	670407.45	3.71	.0724
Speed*Frequency	2	72042.15	3.86	.0672

* $p \leq .05$

Table 32. Means and standard deviations of L5/S1 compression (N) by frequency, %MAWL and speed for Experiment 1.

Frequency (lpm)	Lifting Speed		
	Normal	Fast	% Increase (Fast/Normal)*100
1	6476 ± 1343	8041 ± 1633	124
4	6006 ± 1083	7882 ± 1248	131
8	6217 ± 1217	7151 ± 1190	115
Load (%MAWL)			
35	5224 ± 748	6812 ± 1344	130
60	6653 ± 1391	8100 ± 988	122
85	6626 ± 1025	8162 ± 1457	123
		Mean % Increase	124

Table 33. Mean, standard deviation and range of the peak L5/S1 compression (N) during the pull phase by speed, frequency, and %MAWL for Experiment 1.

Freq (lpm)	MAWL (%)	Lifting Speed Normal Mean	S.D.	Min	Max	Fast Mean	S.D.	Min	Max
	35	5649	785	4316	6602	7117*	1566	4212	9026
1	60	7136*	1628	5452	10447	8463*	703	7333	9622
	85	6642*	1127	5238	8107	8543*	2054	5412	11022
	35	5184	725	4168	6370	6986*	1222	5093	8646
4	60	6400*	1097	5197	8461	8366*	1007	6867	9516
	85	6434*	962	4949	7941	8295*	1081	7500	10681
	35	5428	737	4545	6756	6334*	1217	4609	8415
8	60	6421*	1412	4959	8507	7471*	986	6627	8930
	85	6801*	1057	5564	8550	7647*	990	6491	9339

* Compression force is above the 637 kg maximum tolerance limit as defined by Jager and Luttman (1989) or 650 kg specified by NIOSH (1981).

Table 34. Model and significant effects summary for L5/S1 compression in Experiment 2.

Source	df	Sum of Squares	F Value	PR>F
Model	49	2913504.26	28.51	0.0001
Error	50	104278.83		
Corrected Total	99	3017783.08		
R Square	96%			
Speed	1	1049579.76	18.10	.0131 *
Load	4	683789.21	29.12	.0001 *

* $p \leq .05$

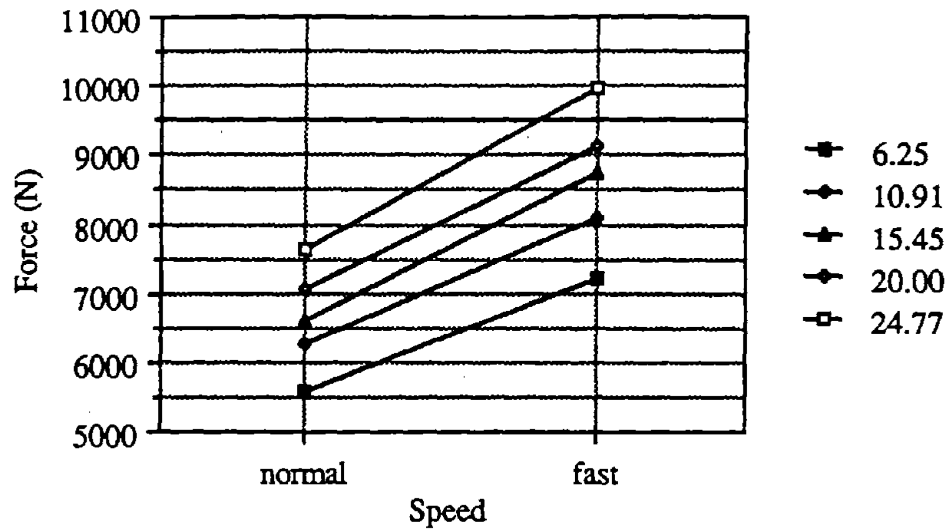


Figure 71. Speed and load interaction on L5/S1 compression forces calculated with measured hand forces for normal and fast lifting.

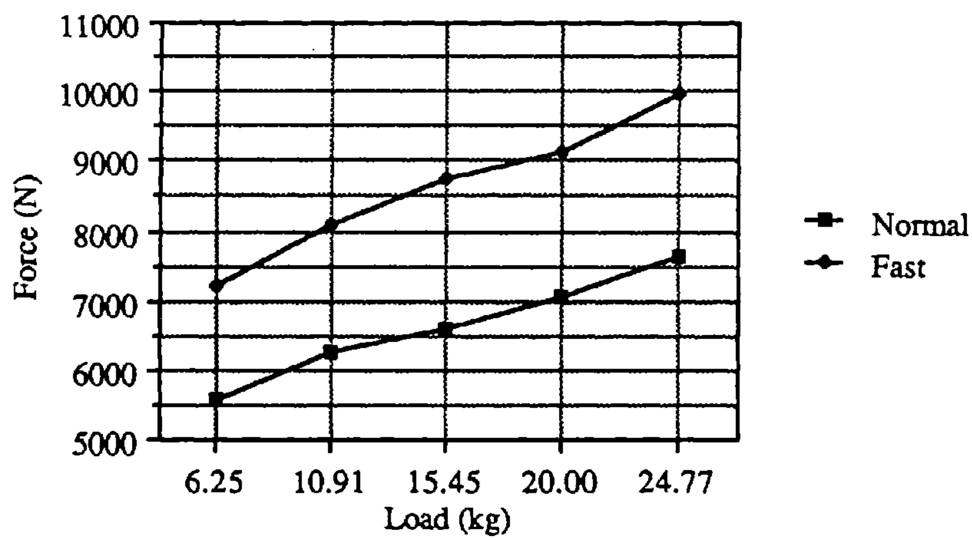


Figure 72. Load and speed interaction on L5/S1 compression forces calculated with measured hand forces for normal and fast lifting.

Table 35. Means and standard deviations of L5/S1 compression (N) by load and speed for Experiment 2.

Load (kg)	Lifting Speed		% Increase
	Normal	Fast	(Fast/Normal)*100
6.25	5586 ± 661	7201 ± 915	129
10.91	6265 ± 831	8114 ± 1234	129
15.45	6604 ± 541	8753 ± 1279	132
20.00	7045 ± 822	9138 ± 1413	130
24.77	7623 ± 827	9957 ± 2181	131
		Mean % Increase	130

kN (445 ± 192 kg) (Jager and Luttman, 1989) and the NIOSH (1981) recommendation of maximum lift exposure of 6.4 kN (650 kg). Only lifts with loads of 6.25 and 10.91 kg at normal speed resulted in average peak L5/S1 compression forces less than the tolerance limits and NIOSH guideline. All other lifts, notably including 6.25 and 10.91 kg loads, at fast speed resulted in L5/S1 compression forces greater than 6400 N. The heaviest load of 24.77 kg lifted at fast speed resulted in average peak L5/S1 compression of 9957 N with a standard deviation of 2181 N.

The model statement shown in Table 36 for L5/S1 shear indicates that speed, load, and their interaction were significant effects at significance levels of .0051, .0001 and .0244, respectively. Plots of speed and load are shown in Figures 73 and 74. As shown in Figures 73 and 74 peak L5/S1 shear increased at an increasing rate as the load became heavier. Table 37 lists the mean and standard deviation corresponding to Figures 73 and 74. For Experiment 2, the magnitude of the shear force never exceeded 1568 N which is only 167 N less than the tolerance limit of 1.735 kN (177 kg) recommended by Farfan et al. (1976).

Time to Complete the Lift

Time to complete the lift was defined as the time elapsed between the first moment that the entire box cleared the floor to the first moment that the entire box reached the destination. Results from Experiment 1 indicate that speed, frequency and the speed/frequency interaction were significant effects on time to complete the lift at significance levels of .0001, .0149 and .0298, respectively. The model summary for time to complete the lift for Experiment 1 is listed in Table 38. The variable %MAWL was not a significant effect. The interaction effect of speed and frequency indicated that lift time does not change equally

Table 36. Model and significant effects summary for L5/S1 shear in Experiment 2.

Source	df	Sum of Squares	F Value	PR>F
Model	49	71998.03	31.07	0.0001
Error	50	2364.35		
Corrected Total	99	74362.38		
R Square	97%			
Speed	1	25344.32	30.85	.0051 *
Load	4	11302.22	17.60	.0001 *
Speed*Load	4	1918.90	3.75	.0244 *

* $p \leq .05$

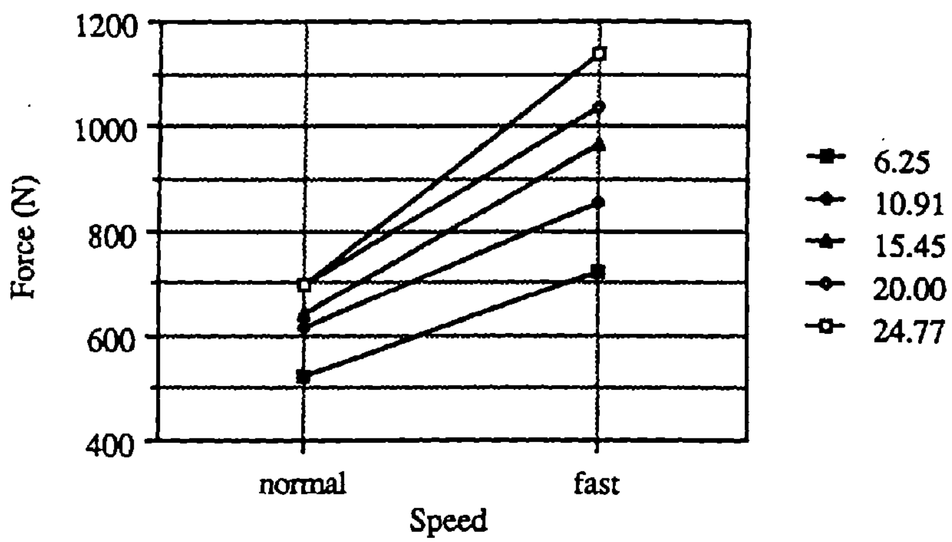


Figure 73. Speed and load interaction on L5/S1 shear forces calculated with measured hand forces for normal and fast lifting.

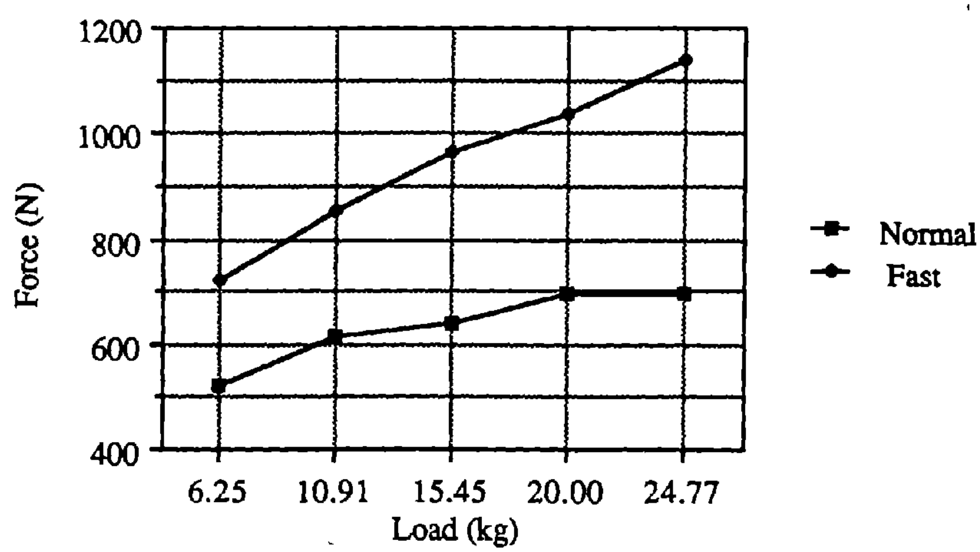


Figure 74. Load and speed interaction on L5/S1 shear forces calculated with measured hand forces for normal and fast lifting.

Table 37. Means and standard deviations of L5/S1 shear (N) by load and speed for Experiment 2.

Load (kg)	Lifting Speed		% Increase
	Normal	Fast	(Fast/Normal)*100
6.25	520 ± 133	719 ± 148	138
10.91	612 ± 148	855 ± 202	140
15.45	640 ± 110	968 ± 213	151
20.00	694 ± 137	1035 ± 262	149
24.77	694 ± 221	1141 ± 293	164
		Mean % Increase	148

Table 38. Model and significant effects summary for time to complete the lift in Experiment 1.

Source	df	Sum of Squares	F Value	PR>F
Model	89	19.27	24.38	.0001
Error	90	.80		
Corrected Total	179	20.07		
R Square	96%			
Speed	1	13.03	340.53	.0001 *
Frequency	2	1.28	7.45	.0149 *
Speed*Frequency	2	.62	5.63	.0298 *

* $p \leq .05$

over the levels of speed for each level of frequency. Figures 75 and 76 illustrate the speed and frequency interaction with the corresponding values of the plots listed in Table 39.

Figures 75 and 76 show that at fast speeds there was not as much difference between lift times at the three frequencies. This difference is at most an average of .07 sec. This may be because the lower frequencies (1 and 4 lpm) did not cycle enough to limit actual lifting time and the lifter is, in effect, lifting as fast as possible regardless of frequency. At fast lifting, the subjects lifted fastest at 8 lpm at .91 sec, and at .98 sec for both 1 and 4 lpm. At normal speeds the differences in time to complete the lift are greater, especially between 1 and 8 lpm. This may indicate that at normal speed of lift the frequency of 8 lpm may limit the time required by the subject to execute the lift. Normal speed of lift at frequencies of 1 and 4 lpm are approximately equal with means of 1.57 and 1.61 sec, but the mean normal speed of lift for 8 lpm is 1.29 sec.

Tables 40 and 41 list the model information and means of time to complete the lift by speed and load for Experiment 2. For Experiment 2, lift times performed at 1 lpm were significantly affected by speed at a .0059 level of significance. Load was not a significant main effect. Figures 77 and 78 illustrate interaction of load and speed. Over the five loads time to complete a lift was an average of 71.3% less than time to complete a lift at normal speed. Although load was not a significant main effect, there was a noticeable difference in time to complete a lift between the lightest (6.27 kg) and heaviest loads for both normal and fast speeds of lift.

In summary, at normal lifting speeds, lifts at slower frequencies (1 and 4 lpm) were executed in approximately the same period of time; the normal speed of lift at 8 lpm was approximately 20% faster. For fast lifting at 1, 4 and 8 lpm the subjects lifted 40, 40 and 30% faster, respectively, than when lifting at the normal speed of lift. Within the 1 lpm frequency, load did not significantly affect time to complete the lift, although time to complete the lift for the lightest load was an average of .24 sec less than for the heaviest

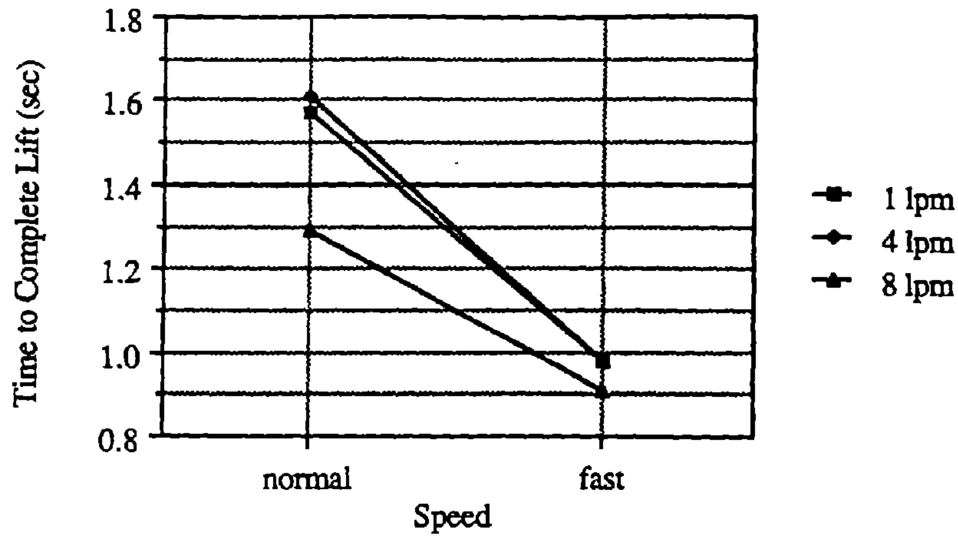


Figure 75. Speed and frequency interaction on time to complete the lift for normal and fast lifting.

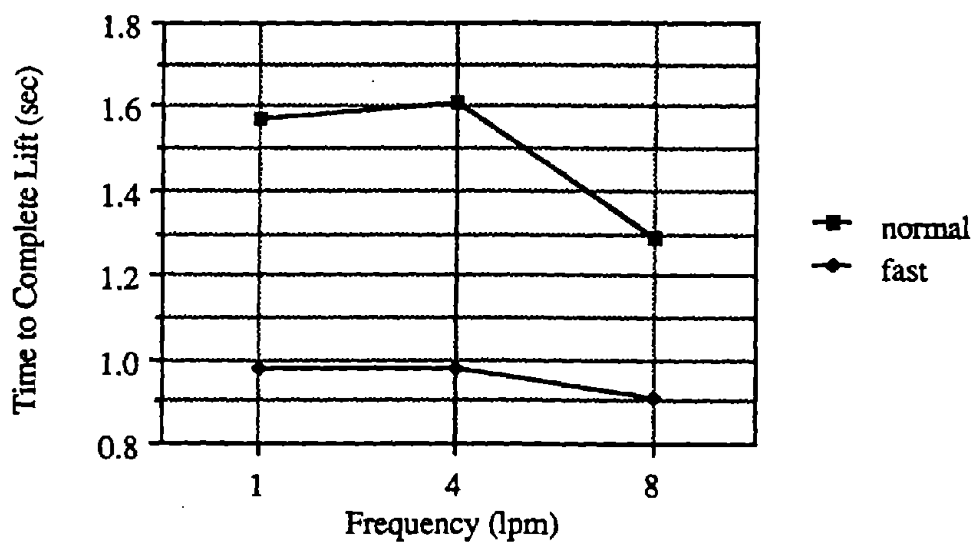


Figure 76. Frequency and speed interaction on time to complete the lift for normal and fast lifting.

Table 39. Means and standard deviations of time to complete the lift (seconds) by speed and frequency for Experiment 1.

Frequency (lpm)	Lifting Speed		% of Normal
	Normal	Fast	(Fast/Normal)*100
1	1.57 ± .21	.98 ± .14	62
4	1.61 ± .24	.98 ± .11	61
8	1.29 ± .18	.91 ± .09	71
		Mean % of Normal	65

Table 40. Model and significant effects summary for time to complete the lift in Experiment 2.

Source	df	Sum of Squares	F Value	PR>F
Model	49	6.48	22.01	.0001
Error	50	.30	.006	
Corrected Total	99	6.78		
R Square	96%			
Speed	1	4.29	28.49	.0059 *
Load	4	.094	2.71	.0677

* $p \leq .05$

Table 41. Means and standard deviations of time to complete the lift (seconds) by speed and load at 1 lpm for Experiment 2.

Load (kg)	Lifting Speed		% of Normal
	Normal	Fast	(Fast/Normal)*100
6.25	1.21 ± .22	.93 ± .14	77
10.91	1.42 ± .20	.95 ± .14	67
15.45	1.34 ± .19	.99 ± .10	74
20.00	1.35 ± .17	.96 ± .12	71
24.77	1.45 ± .20	.98 ± .06	68
		Mean % of Normal	71

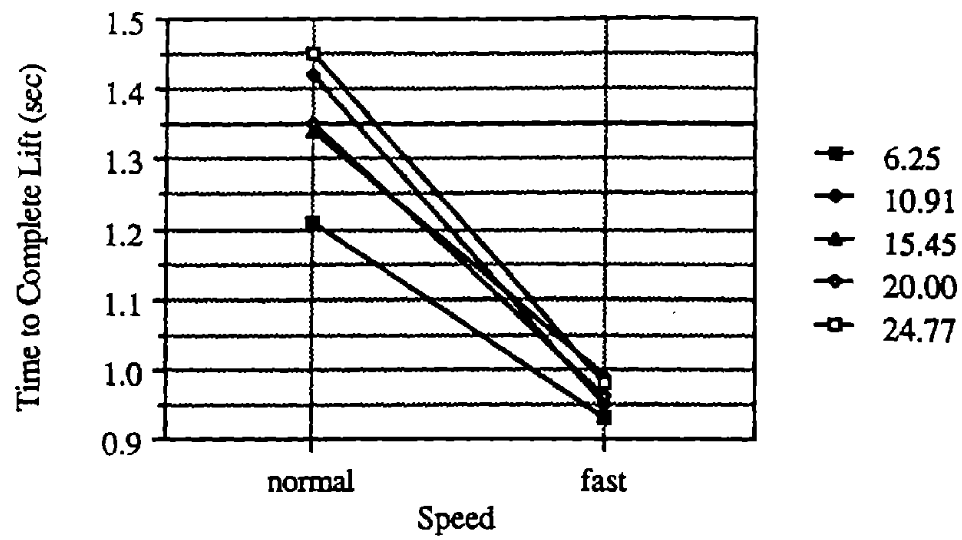


Figure 77. Speed and load interaction on time to complete the lift for normal and fast lifting.

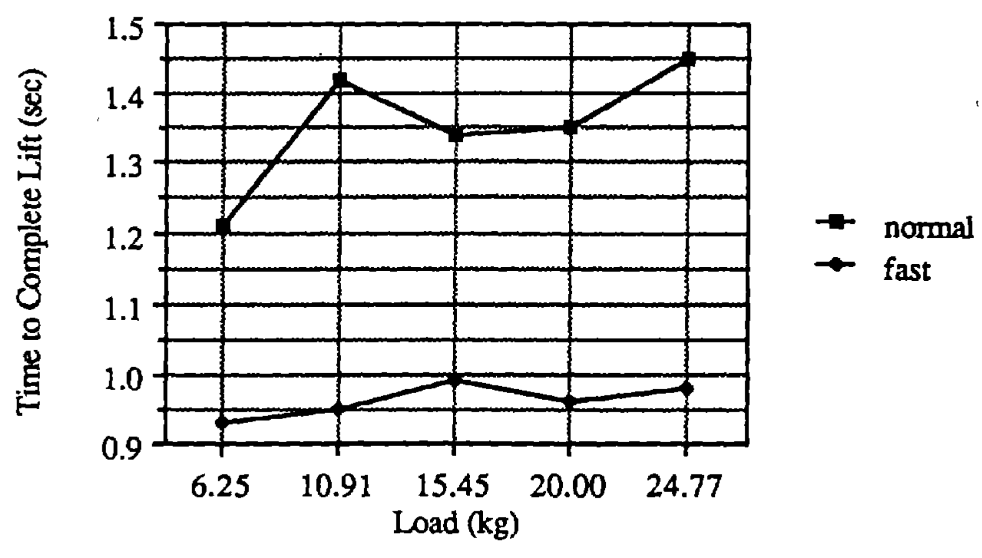


Figure 78. Load and speed interaction on time to complete the lift for normal and fast lifting.

load. The lightest load of 6.25 kg was lifted in less time than the 24.77 kg load for both the normal and fast lifting speeds, .24 and .05 sec, respectively.

Summary

The results are summarized and discussed below.

1. MAWL determined at 1, 4 and 8 lpm by the subjects in this study are in agreement with those MAWLs reported by other investigators at comparable frequencies (Ayoub et al., 1978; Ayoub & Mital, 1990; Mital, 1984; Snook, 1978). Mean MAWLs for this study (N=5) were 35.69 $\pm$ 8.88 kg, 27.52 $\pm$ 5.48 kg and 17.80 $\pm$ 2.10 kg for 1, 4 and 8 lpm, respectively. The MAWL reported here for 1 lpm is substantially higher than reported by Mital (1984). This is probably due to the subjects in Mital's study being industrial workers, not college males.

2. The measured peak applied forces by the hands to the load were consistently greater than the model-calculated reaction forces at the hands for Experiments 1 and 2. Differences between the measured and model-calculated forces were significant for vertical and horizontal applied forces at normal and fast speeds of lift. The difference between measured peak forces and modeled peak forces were greater for fast speed of lift than for the normal speed of lift. For Experiment 1, measured vertical forces at the hands ranged from 108 to 134% of those modeled for normal speed, and 140 to 158% of those modeled for fast speed. For the horizontal forces at the hands, the measured values were up to eight times greater than the modeled values for both fast and normal speeds of lift. For experiment 2, measured vertical forces at the hands ranged from 119 to 136% of those modeled forces for normal speed, and 158 to 178% of those modeled for fast speed. For the horizontal forces at the hands, the measured values were up to seven times greater than the modeled values for both the fast and normal speeds of lift.

3. The calculated peak compression L5/S1 forces using measured applied hand forces as input were up to 10% greater than the model calculated L5/S1 forces with the exceptions of the following lifting tasks: Experiment 1: normal speed of lift 85% MAWL at 1 lpm and 35, 60 and 85% MAWL at 4 lpm; and for Experiment 2: normal speed of lift at 6.25 kg. For these tasks the mean peak L5/S1 compression forces calculated with measured forces were within ± 3%. The small differences between the peak L5/S1 compression forces calculated with measured forces and calculated with the model were not significant for the normal speed of lift; therefore, the L5/S1 peak compression calculated for normal speed was virtually the same, regardless of analysis methods. However, at fast speeds of lift, peak L5/S1 compressions were highly significantly different (ranging from 104 to 111% of modeled) between modeled and modeled with measured input conditions.

According to the plots of measured hand forces over the duration of the lift, in most lifting trials the lifter jerked the load to overcome the inertia of the load resting on the ground. However, the peak in hand forces during the pull phase did not carry through to significantly affect L5/S1 compression and shear for each lifting condition investigated.

4. The calculated peak shear L5/S1 forces using measured applied forces as input were greater than the model calculated L5/S1 shear forces for both fast and normal speeds of lift for both experiments, with the exception of normal speed of lift with 24.77 kg load for Experiment 2. For this task the mean peak shear force calculated with measured values was 1% less than that of the modeled mean peak shear force. These differences between peak L5/S1 shear forces ranging from 108 to 136% of the modeled values, were highly significant for fast and normal speeds of lift.

5. The fast speed of lifting resulted in consistently greater peak hand and L5/S1 forces ranging from increases of 130 to 230% of mean forces at normal speed, regardless of analysis method (measured or modeled) compared to slow speeds of lifting. As shown in other studies, the effects of fast lifting multiplied the effect of the load in terms of L5/S1

compression on the spine (as calculated with measured input) up to 130%. The effect of fast speed lifting was greater for the measured hand forces which were increased up to 230% of the hand forces associated with normal speed lifting.

6. For fast speed of lift, the measured peak applied forces are concentrated near the liftoff -- either four frames before or after; at the normal speed the peak applied forces were more spread out from before the lift off to as much as 29 frames afterwards. This was consistent for horizontal and vertical applied forces as well as compression and shear forces at L5/S1. Even at normal speed, according to the time history of the forces applied to the load, the peak or spike was evident in the plot. This spike was evident immediately near the liftoff, usually within 4/60 (.067) sec before or after the liftoff. The time of the spike appeared to be distributed about the time of liftoff, with several trials during which the spike occurred before liftoff. Therefore, the lifters were exerting forces to the load which resulted in peak L5/S1 compression forces before the load was lifted off the ground. These findings indicate that the compression forces at L5/S1 during the "preparatory" phase of the lift were not due to the acceleration of the load, but rather to the forces applied by the hands of the lifter in a static condition to overcome the inertia of the resting load.

7. The L5/S1 compression and shear forces calculated from measured hand forces as input were, in general, greater than modeled, but the classification of the lift as dangerous based on peak compression or shear at L5/S1 was not changed. Out of the two experiments, only two trials occurred where L5/S1 forces at the lower/release phase were greater than the pull. Therefore, for this study the limiting phase of the lift was the pull phase.

8. All lifts exhibited a spike or peak for hand forces which surpassed the modeled forces, but then dropped below or matched the modeled forces. The measured hand forces also deviate from the modeled values toward the end of the lift, specifically when the lifter placed the load at its destination. The deviations toward the end of the lift were due to the

targeting of the load by the lifter as the load was moved toward its destination. In general, the model appears to account for external forces applied to the load after the load has been picked up to just before the release of the load, regardless of the speed of lift.

9. Data also demonstrated that peak L5/S1 compression forces above 6370 N occurred at light loads of 6.25 and 10.91 kg lifted at fast speed, and 15.45 kg lifted at normal speed. For Experiment 1, the mean peak compression force for all lifting tasks at fast lifting speed were greater than 6370 N, and all lifts at normal speed caused forces greater than 6370 N except 35%MAWL at 1, 4 and 8 lpm. Of these three lifting tasks at normal speed, some individual trials resulted in compression forces at 6370 N or higher. For Experiment 2, all conditions resulted in mean peak compression forces greater than 6370 N except for 6.25 and 10.91 kg loads at normal speed. Of these two loads, some individual lifting trials resulted in calculated peak L5/S1 compression in excess of 6370 N. For the subjects who participated in this study the loads of 6.25 and 10.91 kg were below selected MAWLs at 8 lpm. Therefore, in the context of this study, these loads are called light loads. This is a significant finding since lifting tasks which have light loads and are repetitive in nature are usually considered safe according to biomechanical limits. Lifting tasks at 60 and 85%MAWL at 8 lpm, traditionally classified as physiologically limiting tasks, resulted in mean peak compression forces for normal and fast lifting speeds of 6421 and 7647 N, which are greater than the 6370 N maximum limit recommended by NIOSH (1981). The weight of load for these lifting tasks ranged from 9.68 to 18.21 kg. In view of the results of this study, these light load/high frequency tasks can be especially threatening since the lifter does not feel strength taxed and the lower back is repeatedly exposed to high forces while the lifting task is declared within physiological limits of the cardiovascular system. The high L5/S1 compression forces reported in this study for light loads seem to support the theorized cause of lower back pain: chronic exposure; not traumatic event.

10. For this study, the peak in L5/S1 compression forces as calculated with the measured hand forces as input was the maximum force experienced during the lift for all trials in both experiments. For most trials the peak occurred during the pull phase of the lift (within .067 sec of liftoff). Therefore the pull phase, specifically up to 4/60 sec before and 4/60 sec after liftoff, was the time period during the lift when most peak L5/S1 compression forces occurred. However, in four trials by the same subject, peak L5/S1 shear forces were at the end of the lift during placement of the load at knuckle height. In all other trials and for all other subjects the peak L5/S1 shear occurred at the pull phase of the lift.

11. Experiment 1 investigated the effects of speed, frequency and %MAWL on peak hand and resulting L5/S1 forces. In general, as the speed of the lift is increased from normal to fast, the magnitude of peak hand forces increased at a greater rate with lower frequency. This relationship may be related to the speed and frequency interaction on time to complete the lift, coupled with the heavier loads at lower frequencies. The time required to complete a fast lift was virtually the same for the three lifting frequencies. For the lower frequencies, 1 and 4 lpm, the time to complete a lift at normal speed was the same. However, the lower the frequency, the greater the differences in the time to complete a lift between the normal and fast speeds. This may account for the speed and frequency interaction on peak applied forces by the hands to the load. Percent MAWL was a highly significant effect on peak applied forces applied by the hands to the load, as expected.

Experiment 2 investigated the effects of speed of lift and weight within the frequency of 1 lpm. Speed and load were both significant effects without interaction on the horizontal and vertical hand forces. For the forces at L5/S1, speed of lift was a significant effect on compression and shear forces At 1 lpm, speed and load were both significant effects.

CHAPTER V

CONCLUSION

This study addressed the following three purposes. First, the forces applied to the load by the hands during a floor-to-knuckle lift were measured and compared to those forces calculated by the Dynalift biomechanical model. Next, two experiments were designed to investigate the effects of speed of lift (normal and fast), frequency of lift (1, 4, and 8 lpm), load in terms of percent of MAWL (35, 60 and 85%), and load in terms of weight (6.25, 10.19, 15.45, 20.00 and 24.77 kg) on the forces applied by the hands to the load and the resulting modeled compression and shear forces at the low-back (defined as the L5/S1 joint). Finally, the moment in time during the pull phase of the lift at which the peak forces occurred was determined in order to identify the time of the lift which was most limiting to the lifter in terms of forces acting at the low-back.

It was hypothesized that the measured peak hand forces would be greater in magnitude than the modeled values, and the independent variables of speed, frequency, %MAWL and load were expected to have significant effects on the applied forces. It was hypothesized that the measured hand forces would exhibit a peaked or spiked pattern at the pull phase. This peaked or spiked pattern was expected to occur due to the nature of the pull phase of the lift in which the lifter must jerk the load to overcome its inertia to lift it off the ground. The evidence of this peak in the hand forces was expected to support the notion that the lifting motion is not a smooth and controlled activity, but rather a jerk is employed by the lifter at the beginning of the lift. It was also expected that peak hand forces would occur immediately before, at, or immediately after the lift off of the load from the ground.

These hypotheses were addressed in four phases of the study. Phase I involved recruiting and training of the 5 male subjects, 18 to 29 years of age. Phase II involved determination of the subjects' MAWLs for each frequency of lift. In Phase III A/D and video data were collected for Experiments 1 and 2, and in Phase IV the data were biomechanically and statistically analyzed.

Measurement of the applied forces to the load was accomplished with an apparatus which simulated a box-type container with dimensions 18 x 12 x 12 inches, and was an aluminum frame which could be loaded from 5.68 kg (empty) to 49 kg (maximum load). The apparatus was instrumented with strain gages on the left handle so that forces applied to the handle in both the horizontal and vertical directions could be determined. The strain gage A/D data was synchronized with joint displacement data in time series for the entire lift. The exact data point at which the load left the ground was also recorded.

Experiment 1 investigated the effects of speed of lift (normal and fast) frequency (1, 4 and 8 lpm) and %MAWL (30, 60 and 85%) on the measured hand forces and the resulting forces at the low-back. Statistical analysis of the data showed that speed, frequency and %MAWL had significant effects on peak horizontal and vertical hand forces and L5/S1 shear force. Only speed had a significant effect on peak L5/S1 compression forces calculated with input of measured hand forces. For the vertical hand forces, speed and frequency interacted so that as speed of lift increased from normal to fast the peak hand forces increased at greater rate with lower frequency.

Experiment 2 investigated the effects of speed of lift and load of the container lifted at 1 lpm on the measured hand forces and the resulting calculated forces at the low-back. Statistical analysis of the data showed that speed and load had significant effects without interaction on the measured peak hand forces. For forces at L5/S1, speed and load had significant effects on L5/S1 peak compression and shear, as well as a speed and load interaction effect on shear.

Comparison of the measured peak hand forces and the modeled peak hand forces showed that a peak was evident in most lifting trials indicating that the subjects jerked the load to overcome inertia of the load resting on the ground. This occurred even for light loads. However, the peak did not carry through to affect L5/S1 compression and shear for each lifting condition investigated in this study. In general, the heavier or faster the lift, the more evidence of the steep spike in force on L5/S1 during the pull phase of the lift. Also, the faster the lift, the more centralized the time of peak forces (applied and L5/S1) around the moment of liftoff, and the greater the proportion of the peak forces occurred before or at liftoff.

In general, the model appeared to account for forces applied to the load after it left the ground and before it was lowered and released at knuckle height. However, at the pull phase, the model significantly underestimated the hand forces applied to the load during the pull phase of the lift for both fast and normal speeds of lift. With the measured hand forces as input, the resulting calculated L5/S1 forces were significantly greater than modeled peak L5/S1 compression and shear forces only for the fast speed of lift.

The results of this study yield practical implications regarding floor-to-knuckle height lifting at fast and slow speeds. The peaks in applied forces during the pull stage indicated that the subjects of this study jerked the load from the ground to overcome inertia of the load. The magnitude of the peak hand force resulting from the jerk in general increased for heavier weight and faster lifting speed. However, the peak in hand force was only "transferred" as a significant increase in peak magnitude of L5/S1 forces for fast lifts. The peak in this case was significantly greater than the maximum modeled by Dynalift. For normal speed of lift shallow peaks in L5/S1 forces were detected for heavier lifts and lower frequency, but the magnitude of the measured peak was not statistically greater than the modeled maximum at normal speed of lift.

In view of these results, the necessity to revise the model to account for these applied forces during the pull phase (and during the lower/release phase) of floor-to-knuckle height lifting depends on the purpose of the analysis. If the Dynalift model is being used to determine the maximum compression at L5/S1 and the approximate time at which it occurs, then the model appears to be adequate if the lift is executed at normal speed, despite the result that the model tends to insignificantly underestimate this value. However, if the purpose of the model is to accurately model the links in detail at each frame, then the Dynalift model should be revised to account for deviations in measured hand forces detected in this study for both the pull phase and the lower/release phase of the floor-to-knuckle lift. For fast speeds of lift, the model underestimated peak L5/S1 compression and is not capable of showing that the peak occurred before liftoff.

This research points to practical implications for safety and training of the worker performing manual material handling tasks. It appears that for some fast and heavy lifting conditions, the steep peak in L5/S1 compression forces calculated by the biomechanical model with input of measured hand forces is not due to the acceleration effect (which the smooth and continuous recommendation by NIOSH is supposed to counteract), but rather due to the hand forces being applied by the lifter to the load while it is not yet lifted off the floor. Other practical implications indicated in this study for the lifter are that the pull stage was the limiting phase of the lift and that light loads lifted at repetitive frequencies are also associated with dangerous compression forces at L5/S1.

Recommendations for Future Study

1. Repetition of this study with a load cell may improve the accuracy of the direct hand force measurements over the strain gage method, due to the degrees of freedom in placement of strain gages on the handle.

2. Since only the floor-to-knuckle height lifting range was investigated in this study, data must be collected at the other lifting ranges as well, to determine if the magnitudes and relationships of the hand forces behave consistently for these loads, frequencies and speeds of lift.

3. The peak in hand forces was a common phenomenon for all lifting tasks in this study and it appeared necessary that the lifters jerk the load to overcome its inertia. The jerk is known to increase compression at L5/S1, so it would be desirable to train the subjects with feedback to attempt lifting without using the jerk, and compare the maximum acceptable weight achieved when lifting without the jerk.

4. Collection of frame by frame data for several lifting conditions would provide enough information to generate a simulated peak hand force pattern since it appears that the peak is not discernible from displacement data.

5. Revision of the model to include algorithms for modeling hand forces will require further research. As shown in this study, the hand forces are affected by several variables and their interactions. Further development of algorithms to supplement a dynamic biomechanical model will require higher resolution of data by using a faster sampling speed in order to more accurately pinpoint the time of liftoff and corresponding hand forces.

REFERENCES

Anderson, C. K., Chaffin, D. B., Herrin, G. D. & Matthews, L. S. (1985). A biomechanical model of the lumbosacral joint during lifting activities. Journal of Biomechanics, 18(8), 571-584.

Armstrong, J. R. (1965). Lumbar disc lesions. Baltimore: Williams and Wilkins Co.

Ayoub, M. M. (1987). The problem of manual materials handling. In S. S. Asfour (Ed.), Trends in Ergonomics/Human Factors IV (pp. 925-931). Amsterdam, Netherlands: North-Holland.

Ayoub, M. M., Bethea, N. J., Deivanayagam, S., Asfour, S. S., Bakken, G. M., Liles, D., Mital, A., & Sherif, M. (1978). Final report: Determination and modeling of lifting capacity (Grant Nos. 1R010H00545-01 SOH and 5R010H-00545-02). Lubbock: Texas Tech University, Institute for Ergonomics Research.

Ayoub, M. M., Chen, H. C., & Coss. R. (1986). Dynamic modeling for manual material handling in the sagittal plane: A manual for the software package Dynalift. Lubbock: Texas Tech University, Institute for Ergonomics Research.

Ayoub, M. M., Dryden, R. D., & McDaniel, J. W. (1975). Models for lifting activities. In R.C. Nelson & C. A. Morehouse (Eds.), Biomechanics IV (pp. 30-36). Baltimore, MD: University Park Press.

Ayoub, M. M., & El-Bassoussi, M. M. (1976). Dynamic biomechanical model for sagittal lifting activities. Proceedings of the 6th Congress of the International Ergonomics Association (pp. 355-359). Santa Monica, CA: The Human Factors Society.

Ayoub, M. M., & Mital, A. (1990). Manual Materials Handling. New York : Taylor & Francis.

Ayoub, M. M., Mital, A., Asfour, S. S., & Bethea, N. J. (1980). Review, evaluation, and comparison of models for predicting lifting capacity. Human Factors, 22(3), 257-269.

Baumann, W., Gross, V., Quade, K., Galbierz, P., & Schwirtz, A. (1988). The snatch technique of world class weightlifters at the 1985 World Championships. International Journal of Sport Biomechanics, 4, 68-89.

Bean, J. C. & Chaffin, D. B. (1988). Biomechanical model calculation of muscle contraction forces: A double linear programming method. Journal of Biomechanics, 21(1), 59-66.

Bejjani, F. J., Gross, C. M., & Pugh, J. W. (1984). Model for static lifting: Relationship of loads on the spine and knee. Journal of Biomechanics, 17(4), 281-286.

Brinckmann, P., Biggermann, M. & Hilweg, D. (1988). Fatigue fracture of human lumbar vertebrae. Clinical Biomechanics, Supplement No.1.

Brown, E. W., & Abani, K. (1985). Kinematics and kinetics of the dead lift in adolescent power lifters. Medicine and Science in Sports and Exercise, 17(5), 554-563.

Bryant, J. T., Stevenson, J. M., French, S. L., Greenhorn, D. R., Andrew, G. M., & Deakin, J. M. (in press). Four factor model to describe an isoinertial lift. Ergonomics.

Burdett, R. G. (1982). Biomechanics of the snatch technique of highly skilled and skilled weightlifters. Research Quarterly for Exercise and Sport, 53(3), 193-197.

Bureau of Labor Statistics. (1982). Back injuries associated with lifting. (U. S. Department of Labor Bulletin 2144). Washington, D.C.: U.S. Government Printing Office.

Bush-Joseph, C., Schipplein, O., Andersson, G. T. & Andriacchi, T. P. (1988). Influences of dynamic factors on the lumbar spine movement in lifting. Ergonomics, 31(2), 211-216.

Centers for Disease Control. (1983). Leading work-related diseases and injuries - United States. Morbidity and Mortality Weekly Report, 32(14), 189-191.

Chaffin, D. B. (1969). A computerized biomechanical model - development and use in studying gross body actions. Journal of Biomechanics, 2, 429-441.

Chaffin, D. B., & Andersson, G. (1984). Occupational biomechanics. New York: John Wiley & Sons.

Chaffin, D. B., & Baker, W. H. (1970). A biomechanical model for analysis of symmetric sagittal plane lifting. AIIE Transactions, 2(1), 16-27.

Chaffin, D. B., Fisher, B., Hodges, W. & Miyamoto, R. (1967). A biomechanical analysis of materials handling activities performed in the sagittal body plane. Technical Report, Center for Ergonomics, University of Michigan.

Chen, H. C. & Ayoub, M. M. (1988). Dynamic biomechanical model for asymetric lifting. In F. Aghazadeh (Ed.), Trends in Ergonomics/Human Factors V (pp. 879 - 886). Amsterdam, Netherlands: North-Holland.

Eklund, J. E., & Corlett, E. N. (1984). Shrinkage as a meaure of the effect of load on the spine. Spine, 9, 189-194.

El-Bassoussi, M. M. (1974). A biomechanical model for lifting in the sagittal plane. Unpublished doctoral dissertation, Texas Tech University, Lubbock.

Enoka, R. M. (1979). The pull in Olympic weightlifting. Medicine and Science in Sports, 11(2), 131-137.

Evans, F. G. & Lissner, H. R. (1959). Biomechanical studies on the lumbar spine and pelvis. Journal of Bone and Joint Surgery, 41(A), 2.

Farfan, H. F. (1970). The effects of torsion on the lumbar intervertebral joints: The role of torsion in the production of disc degeneration. Journal of Bone Joint Surgery, 52(A), 468-483.

Fernandez, J. E. (1986). Psychophysical lifting capacity over extended periods. Unpublished doctoral dissertation, Texas Tech University, Lubbock.

Fitzgerald, J. G. (1972). Changes in spinal stature following brief periods of shoulder loading. Royal Air Force Institute of Aviation Medicine, IAM Report No. 514.

Freivalds, A., Chaffin, D., Garg, A., & Lee, K. (1984). A dynamic biomechanical evaluation of lifting maximum acceptable loads. Journal of Biomechanics, 17(4), 251-262.

Garhammer, J. (1980). Power production by Olympic weightlifters. Medicine and Science in Sports and Exercise, 12(1), 54-60.

Garhammer, J. (1982). Energy flow during Olympic weightlifing. Medicine and Science in Sports and Exercise, 14(5), 353-360.

Garg, A. (1987). A psychophysical, physiological and biomechanical evaluation of NIOSH guidelines for manual handling. In S. S. Asfour (Ed.), Trends in Ergonomics/Human Factors IV (pp. 925-931). Amsterdam, Netherlands: North-Holland.

Garg, A., & Chaffin, D. B. (1975). A biomechanical computerized simulation of human strength. Transactions of the American Institute of Industrial Engineers, 7(1), 1-15.

Garg, A., Chaffin, D. B., & Freivalds, A. (1982). Biomechanical stresses from manual load lifting: A static vs dynamic evaluation. IIE Transactions, 14(4), 272-281.

Garg, A., Mital, A., & Asfour, S. S. (1980). A comparison of isometric strength and dynamic lifting capability. Ergonomics, 23(1), 13-27.

Garg, A., Sharma, D., Chaffin, D., & Schmidler, J. (1983). Biomechanical stresses as related to motion trajectory of lifting. Human Factors, 25(5), 527-539.

Grieve, D. W. (1975). Dynamic characteristics of man during crouch- and stoop-lifting. In R. C. Nelson & C. A. Morehouse (Eds.), Biomechanics IV (pp. 19-29). Baltimore, MD: University Park Press.

Gudmundson, B. R. (1985). Transducers for accurate positioning. Mechanical Engineering, May, Reprint.

Hicks, C. R. (1982). Fundamental concepts in the design of experiments (3rd ed.). New York: Holt, Rinehart, & Winston.

Jager, M. & Luttman, A. (1989). Biomechanical analysis and assessment of lumbar stress during load lifting using a dynamic 19-segment human model. Ergonomics, 32(1), 93-112.

Klein, B. P., Jensen, R. C., & Sanderson, L. M. (1984). Assessment of workers' compensation claims for back strains/sprains. Journal of Occupational Medicine, 26(6), 443-448.

Krusen, F., Ellwood, C. M., & Kottke, F. J. (1965). Handbook of physical medicine and rehabilitation. Philadelphia: W. B. Saunders, p. 608.

Leskinen, T. J., Stalhammar, H. R., & Kuorinka, I. A. (1983). A dynamic analysis of spinal compression with different lifting techniques. Ergonomics, 26(6), 595-604.

Martin, J. B., & Chaffin, D. B. (1972). Biomechanical computerized simulation of human strength in sagittal-plane activities. AIIE Transactions, 4(1), 19-28.

McGill, S. M., & Norman, R. W. (1985). Dynamically and statically determined low back moments during lifting. Journal of Biomechanics, 18(12), 877-885.

Measurements Group Education Division. (1983). Student manual for strain gage technology (Bulletin 309A). Raleigh, NC: Measurements Group, Inc.

Mital, A. (1984). Comprehensive maximum acceptable weight of lift database for regular 8-hour workshifts. Ergonomics, 27, 1127-1138.

Miller, D. I., & Nelson, R. C. (1973). Biomechanics of sport. Philadelphia: Lea & Febiger.

Morris, J. M., Lucas, D. B., & Bressler, B. (1961). Role of the trunk in stability of the spine. Journal of Bone Joint Surgery, 43(A), 327-351.

National Institute of Occupational Safety and Health. (1981). Work practices guide for manual lifting. (DHHS (NIOSH) Publication No. 81-122). Washington, D.C.: U.S. Government Printing Office.

Omega Engineering, Inc. (1988). Pressure, strain and force. Stamford, CT: Author.

Park, K. S., & Chaffin, D. B. (1974). A biomechanical evaluation of two methods of manual load lifting. AIIE Transactions, 6(2), 105-113.

Park, K. S., & Chaffin, D. B. (1975). Prediction of load-lifting limits for manual materials handling. Professional Safety, 20(5), 44-48.

Prunk, C. N. A. (1981). Technical note: Measuring hand-grip force, using a new application of strain gages. Medical and Biological Engineering and Computing, 19, 127-128.

Roozbazar, A. (1975). Biomechanics of lifting. In R. C. Nelson & C. A. Morehouse (Eds.), Biomechanics IV (pp. 37-43). Baltimore, MD: University Park Press.

Rowe, M. L. (1969). Low back pain in industry: A position paper. Journal of Occupational Medicine, 11, 161-169.

Schultz, A. B., Andersson, G. B., Haderspeck, K., Ortengren, R., Nordin, M. & Bjork, R. (1982). Analysis and measurement of lumbar trunk loads in tasks involving bends and twists. Journal of Biomechanics, 15(9), 669-675.

Slote, L., & Stone, G. (1963). Biomechanical power generated by forearm flexion. Human Factors, 5, 443-452.

Snook, S. H. (1978). The design of manual handling tasks. Ergonomics, 21, 963-985.

Smith, J. L., Smith, L. A., & McLaughlin, T. M. (1982). A biomechanical analysis of industrial manual materials handlers. Ergonomics, 25, 299-308.

Snook, S. H., & Ciriello, V. M. (1972). Low back pain in industry. ASSE Journal, 17(4), 17 - 23.

Snook, S. H., & Ciriello, V. M. (1974, May 2). Maximum weights and work loads acceptable to female workers. Paper presented at the American Industrial Health Conference, Miami, FA.

Sonoda, T. (1962). Studies on the compression, tension and torsion strength of the human vertebral column. Journal of Kyoto Prefect Medical University, 71, 659-702.

Stevenson, J. M. (in press). Dynamic analysis of isoinertial lifting technique. Ergonomics.

Tichauer, E. R. (1971). A pilot study of the biomechanical lifting in simulated industrial situations. Journal Safety Research, 3, 98-115.

Troup, J. G., Leskinen, T. J., Stalhammar, H. R., & Kuorinka, I. A. (1983). A comparison of intraabdominal pressure increases, hip torque, and lumbar vertebral compression in different lifting techniques. Human Factors, 25(5), 517-525.

Vojtecky, M. A., Harber, P., Sayre, J. W., Billet, E., & Shimozaki, S. (1987). The use of assistance while lifting. Journal of Safety Research, 18(2), 49-56.

Winter, D. A. (1979). Biomechanics of human movement. New York: John Wiley & Sons.

APPENDIX A: CONSENT AND HISTORY FORMS

Personal Data and Consent Form
Texas Tech University
Institute for Ergonomics Research

Kinematics and Kinetics Investigation of the Pull Phase of Lifting Date __________

ID __________

Name ____Age __________

Sex ___________ Weight (lb) _____________ Height (ft in) _____________

In case of emergency contact: Name ______________Phone(s) _______________

Check if susceptible to:
Shortness of breath ____ Dizziness ____ Headaches ____

Fatigue ____ Pain in arm, shoulder or chest ____

If you checked any of the items above, please explain:

____

Have you every had a heart attack? _____ If so, give history:

____

Are you currently taking any type of medication? ____ If so, please explain:

____

Have you had or do you now have any problems with your blood pressure? ____ If so, please explain:

____

In the last 6 months, have you had any type of surgery or serious illness? ____ If so, please explain:

____

____

In the last 6 months, have you had any back pain? ____ If so, please explain:

____

Have you had or do you now have a hernia? __Corrective Date: _______________

Have you had or do you now have any knee problems? ____ If so, please explain:

____

Please carefully read and sign the attached consent form.

I have truthfully answered the personal data questions attached to this form to the best of my knowledge. I hereby give my consent for my participation in the research project entitled: Kinematics and Kinetics Investigation of the Pull Phase of Lifting. I understand that the person responsible for this research project is Dr. M. M. Ayoub (806) 742-3543. He or his authorized representative, Mary Danz, (806) 742-3429 has explained that this study has the following objective: to determine external forces applied by the hands during the initial phase of lifting. Dr. M. M. Ayoub or his authorized representative has agreed to answer any inquiries I may have concerning the procedures of the project and has informed me that I may contact the Texas Tech University Institutional Review Board for the Protection of Human Subjects by writing them in care of the Office of Research Services, Texas Tech University, Lubbock, TX 79409, or by calling (806) 742-3884.

Information concerning payment for my participation in this study has been explained to me as follows: (a) hourly wage is $5 per hour, not to exceed 30 hours of work; (b) will be made to me upon completion of my participation in the study; (c) method of disbursement of my wages will be a check from Texas Tech, sent to my home address; (d) in the event of withdrawl from the experiment I will be paid for work completed to date; and (e) the researcher for this study has a right to terminate your participation if you are not cooperative or have conflicting schedule problems.

He or his authorized representative has (1) explained the procedures to be followed and identified those which are experimental and (2) described the attendant discomforts and risks.

Briefly, these procedures involve the following: (a) measurement of various body segment parameters including height, weight, and segment lengths; (b) determination of the amount of weight I can safely lift from floor to knuckle height; and (c) repetitive lifting of various weights less than or equal to my maximum weight at various frequencies of lift. To measure body segment parameters, I will be asked to hold my limbs in certain positions while calipers or tape measures are used for measuring. To measure the amount of weight that I can lift from floor to knuckle height, I will be asked to lift a box that contains weights. After completing a trial I will be asked if I can safely handle more weight. If so, I will add weight to the box and I will repeat the trial. If the box is too heavy I will remove weight and attempt to repeat the trial. I will continue until I have determined that a particular weight is the maximum that I can safely handle. The trials will be carried out at three frequencies of lift. To perform the lifts with varying percentages of my maximum weight, I will be asked to lift the container from floor to knuckle height for 10 repetitions at the specified frequencies of lift.

The risks have been explained to me as follows: muscle sprain or strain, pulled tendons, back pain or strain, hernia, bruises or broken bones if the container or weights are dropped. There are also possible changes such as abnormalities of blood pressure or heart rate. I understand that I will likely experience muscle soreness, especially if I am not used to using muscle groups that I will be utilizing during the experiment.

If this research project causes any physical injury to me, treatment is not necessarily available at Texas Tech University or the Student Health Center, nor is there necessarily any insurance carried by the University or its personnel applicable to cover any such injury. Financial compensation for any such injury must be provided through my own insurance program. Further information about these matters may be obtained from the Office of

Research Services, (806) 742-3884, Room 203 Holden Hall, Texas Tech University, Lubbock, TX 79409.

I understand that I will not derive any therapeutic treatment from participation in this study. I understand that I may discontinue participation in this project at any time without prejudice. I understand that all data will be kept confidential and that my name will not be used in any reports, written or unwritten.

Signature of Subject ______________________________ Date __________

Signature of Project Director/Authorized Representative

____

Signature of Witness to Oral Presentation

____

APPENDIX B: LIFTING FOR MAWL INSTRUCTIONS

Lifting for MAWL:
Tape-recorded Instructions for Subjects

This is not a test to determine your maximum weight lifting capacity. I repeat, this is not a test to determine your maximum weight lifting capacity. Rather, it is a study to find reasonable quantities, I repeat, reasonable quantities, that individuals can lift repetitively throughout the workday.

I want you to imagine that you are on piece work, getting paid for the amount of work that you do, but working a normal eight-hour shift that allows you to go home without feeling "bushed." In other words, I want you to work as hard as you can without straining yourself or without becoming unusually tired, weakened, overheated, or out of breath.

Only you will adjust the workload. If you feel that you can work harder without getting overheated, add more weight to the container. If you feel you are working too hard and could not keep up the rate for eight hours, you should remove some weight from the container. Remember, only you will adjust this workload.

Do not be afraid to make adjustments. You have to make enough adjustments so that you get a good feeling for what is too heavy and what is too light. You can never make too many adjustments, but you can make too few. You will be working today at six different lifting frequencies. You will work at each of these combinations for approximately 40 minutes. A signal will help you in maintaining the proper pace or speed. When you hear the signal, start your lift. Then return to your normal standing posture and wait for the next signal to start the next lift.

Remember . . . This is not a contest. Everyone is not expected to do the same amount of work.

We want your judgment on how hard you can work without becoming unusually tired.

APPENDIX C: DATA SHEET FOR ANTHROPOMETRY AND MAWL

Subject Data

Subject ID ____________________
Anthropometric Measurements — Date ____________

Weight (lb) ___________ Stature (cm) ___________ Stature (in) ___________

Hand (cm) ___________

Forearm (cm) ___________

Upper-arm (cm) ___________

Trunk (cm) ___________

Upper-leg (cm) ___________

Lower-leg (cm) ___________

Abdominal depth (cm) ___________

Maximum Acceptable Weight of Lift (MAWL) — Date ____________

Lifting Frequency		MAWL			
1	_____	_____	_____	_____	_____
4	_____	_____	_____	_____	_____
8	_____	_____	_____	_____	_____

APPENDIX D: STEPS FOR STRAIN GAGE INSTALLMENT

Adhering the Strain Gages to the Handles

Prep the metal (aluminum)

a. Degrease the entire specimen with CSM-1 on a clean gauze sponge.

b. Place a liberal amount of M-Prep Conditioner A in gage area and wet lap with clean 320-grit silicon-carbide paper. Keep surface wet while lapping. When bright surface is produced, wipe dry with a clean surface of a gauze sponge for each stroke.

c. Repeat (b) using 400-grit silicon-carbide paper.

d. Burnish layout lines marking gage location with a medium-hard drafting pencil.

e. Remove residue from step (d). Apply Conditioner A repeatedly and scrub with cotton-tipped applicator until a clean tip is no longer discolored by scrubbing. Keep surface wet until cleaning is completed.

f. Dry the surface with a single slow stroke of a gauze sponge in one direction. Repeat, using a new sponge, in the opposite direction.

g. Neutralize surface with M-Prep Neutralizer 5 by applying to surface and scrubbing with a clean cotton-tipped applicator. Keep the surface wet until finished.

h. Dry surface as in step (f).

i. Install strain gage within 30 minutes.

Strain Gage Bonding DO NOT TOUCH GAGES OR METAL WITH HANDS.
Complete f-g-h in 3-5 sec.

a. Remove strain gage from envelope with tweezers and place on clean glass plate with bonding side down. Place terminals in appropriate location (with space of about 1/16" between gage and terminal).

b. Apply M-Line PCT-2 cellophane tape and pick up gage and terminals at a shallow angle (30-45 degrees).

c. Position the gage and terminals over the specimen and wipe tape onto the specimen.

d. Lift tape at shallow angle leaving opposite end attached to specimen.

e. Apply M-Bond 200 Catalyst sparingly to back of gage and terminals. Let dry 1 minute.

f. Apply 1-2 drops of M-Bond 200 adhesive at junction of tape and specimen.

g. Immediately rotate the tape to 30 degrees and firmly make a single wipe to bring the gage down onto the specimen.

h. Immediately apply firm thumb pressure for at least 1 minute.

i. Wait 2 minutes.

j. Remove tape by peeling it slowly off the surface.

Soldering

a. Clean tip of soldering iron with gauze sponge and tin it with fresh solder.

b. Tin gage tabs and terminal tabs.

c. Melt small amount of solder on tip of iron and lay rosin-core solder wire across the gage tab or terminal. Firmly apply the iron tip for one second, then simultaneously lift both solder and tip.

d. Strip wire with hot tip, tin wire, expose 1/8" tinned wire.

e. Tack wires to specimen with drafting tape and apply solder and iron tip to tinned wire.

f. Apply rosin solvent to solder joints, remove tape.

g. Remove solvent with sponge.

h. Apply protective coating continuously up to and over at least the first 1/8" of lead wires.

i. Check resistance between lead wires - should be resistance of gage.