

**The Effect of Sets and Repetitions on Acceleration
During the Prone Dumbbell Row**

**By
Christopher A. Lewis**

**Submitted To
The Faculty of Graduate Studies
In Partial Fulfillment of the Requirements for the Degree
Masters of Science**

**University of Manitoba,
Faculty of Physical Education and Recreation Studies
December 15, 2000**



National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file *Votre référence*

Our file *Notre référence*

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-57554-3

Canada

**THE UNIVERSITY OF MANITOBA
FACULTY OF GRADUATE STUDIES

COPYRIGHT PERMISSION PAGE**

The Effect of Sets and Repetitions on Acceleration During the Prone Dumbbell Row

BY

Christopher A. Lewis

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree
of
Master of Science**

CHRISTOPHER A. LEWIS © 2000

Permission has been granted to the Library of The University of Manitoba to lend or sell copies of this thesis/practicum, to the National Library of Canada to microfilm this thesis/practicum and to lend or sell copies of the film, and to Dissertations Abstracts International to publish an abstract of this thesis/practicum.

The author reserves other publication rights, and neither this thesis/practicum nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

TABLE OF CONTENTS

TABLE OF CONTENTS	2
ABSTRACT	4
ACKNOWLEDGEMENTS	5
LIST OF FIGURES.....	6
LIST OF EQUATIONS.....	6
LIST OF TABLES.....	7
DEFINITIONS.....	8
INTRODUCTION	13
LITERATURE REVIEW	15
RESISTANCE EXERCISE.....	15
<i>Methods</i>	<i>15</i>
LOAD.....	16
<i>Moment Arm</i>	<i>19</i>
<i>Resultant Joint Moment</i>	<i>20</i>
<i>Dynamometry.....</i>	<i>22</i>
<i>Mathematical Model of Free Weight Exercise</i>	<i>23</i>
<i>Maximal Voluntary Contraction (MVC).....</i>	<i>26</i>
<i>Cadence/Velocity</i>	<i>40</i>
<i>Physiological Components</i>	<i>40</i>
SUMMARY	41
STUDY RELEVANCE.....	42
OBJECTIVES.....	44
HYPOTHESES	45
LIMITATIONS.....	45
ASSUMPTIONS	46
METHODOLOGY	47
EXPERIMENTAL DESIGN.....	47
SUBJECTS	47
<i>Inclusion Criteria.....</i>	<i>47</i>
<i>Exclusion Criteria.....</i>	<i>48</i>
<i>Recruitment.....</i>	<i>48</i>
<i>Ethical approval.....</i>	<i>48</i>
PROCEDURE.....	48
<i>Prone Dumbbell Row.....</i>	<i>49</i>
<i>Familiarization + Warm up.....</i>	<i>50</i>
<i>Exercise Protocol.....</i>	<i>51</i>

<i>Determination of weight for the prone dumbbell row exercise.....</i>	<i>52</i>
ACCELERATION MEASUREMENT PROTOCOL.....	53
INSTRUMENTATION	54
<i>Dumbbell</i>	<i>55</i>
<i>Accelerometer.....</i>	<i>56</i>
ACCELERATION PROFILES	58
<i>Phases of Acceleration.....</i>	<i>58</i>
<i>Standardized Nomenclature for Phases of Motion</i>	<i>58</i>
<i>Acceleration Profiles of Continuous Cyclical Movements.....</i>	<i>61</i>
DATA ACQUISITION.....	63
<i>Low and High Pass Filter Selection</i>	<i>63</i>
<i>Orientation of Accelerometer</i>	<i>65</i>
<i>Analysis.....</i>	<i>66</i>
STATISTICAL ANALYSIS	67
RESULTS.....	68
SUBJECT CHARACTERISTICS.....	68
12 RM TESTING.....	68
CONTINUOUS SETS	68
<i>Repetition Duration</i>	<i>68</i>
<i>Within Set, Inter- Repetition Acceleration Magnitude.....</i>	<i>70</i>
<i>Inter- set comparisons</i>	<i>72</i>
<i>Peak Acceleration Slope.....</i>	<i>72</i>
<i>Peak Accelerations: Phase Magnitude Comparisons.....</i>	<i>73</i>
<i>Peak Accelerations</i>	<i>73</i>
<i>Correlation between P4/P1 and P2/P3.....</i>	<i>77</i>
PEAK ACCELERATIONS DURING CONTINUOUS AND DISCONTINUOUS REPETITIONS.....	79
SUMMARY OF RESULTS	80
DISCUSSION.....	81
CONCLUSION	89
RECOMMENDATIONS FOR RESISTANCE TRAINING.....	89
FUTURE STUDIES.....	90
REFERENCES	92
APPENDIX A: SCREENING ASSESSMENT & QUESTIONNAIRE	98
APPENDIX B: PARAPHRASE	100
APPENDIX C: CONSENT FORM	102
APPENDIX D: EXAGGERATED ACCELERATION PROFILE	103

ABSTRACT

Load is an important parameter in resistance training in rehabilitation, athletic performance and general fitness training. In practice and in research, load assessment during resistance exercises has generally been based upon weight. However, it is known that loading during exercise is related to the joint moment generated during resistance exercise. Acceleration is a key parameter which influences load magnitude but this aspect of loading has not been previously explored. The primary objective of the study was to examine the variation in acceleration within and between sets for a standardized free weight exercise. A secondary objective was to examine differences in acceleration between resistance trained and untrained subjects. **METHODS:** Data was collected on 26 female subjects (18 trained and 8 untrained). Subjects performed a standardized exercise (prone dumbbell row involving 3 sets of 10 repetitions with a 2 minutes inter-set rest, at a 12 repetition maximum weight. A 4th set including 2 momentary pauses - one between each repetition and one at the midpoint of the ROM was also performed. Dumbbell acceleration was recorded using a calibrated uniaxial accelerometer (250 Hz sampling rate). **RESULTS:** The first repetition acceleration magnitude was significantly lower than the second repetition for all sets in the trained group. Peak to peak accelerations increased over repetitions in the first and second sets in the untrained group. However, in the trained group this increase was only observed in the first set. Peak upward acceleration was found to be significantly lower than the peak downward acceleration for all sets and both groups. There was a high positive correlation between the upward acceleration and the downward acceleration magnitude for the trained group. A weak correlation was observed for the untrained group. The range of acceleration values was substantially larger for the trained group (1.6 g) than those of the untrained group (0.7g). The addition of momentary pauses in the exercise resulted in a significant and substantial reduction in peak acceleration. **CONCLUSION:** This study demonstrates that weight alone is inadequate for load assessment and that acceleration dependent loading is a major component of load during free weight resistance training. These findings have implications for training studies and the assessment and prescription of exercise.

ACKNOWLEDGEMENTS

I would like to thank my committee Dr. Ready, Dr. Porter, and Dr. Szturm for their patience.

You guys are the best!

I would especially like to thank my advisor Dr. Kriellaars not only for the help and guidance to complete this project but also for the opportunity to learn so much in the Human Dynamics Laboratory in so many areas, and to become involved in so many fascinating projects.

Dean you're great!

To my lab buddies, a big thank you
You guys are great!

I would finally like to thank my family and friends, in particular Krista
You are not only great
You are the best!

LIST OF FIGURES

Figure 1. RJM_{ELBOW} during the ascent phase of a biceps curl. The RJM_{ELBOW} (diamond symbols) is shown which was derived solely from the moment of the weight of the dumbbell and the body segments. RJM_{ELBOW} (square symbols) is determined using both moment of weight and acceleration.	26
Figure 2. Sequential photographs of the movement sequence for the prone dumbbell row.	49
Figure 3. Warm up stretches. Right hand panel one is a behind the neck stretch. Left hand panel is the in front of neck stretch.	51
Figure 4. Experimental setup. A- Range of motion marker. B-Dumbbell, C-Oscilloscope D- Data acquisition system, E – accelerometer amplifier, F- EMG system.	55
Figure 5. A linear, uniaxial accelerometer and connector system.	56
Figure 6. A representative accelerometer waveform for a calibration trial.....	57
Figure 7. A representative trial for a trained subject showing the band-passed filtered acceleration profile for four sets. The inter-set rest interval is evident between each set.....	58
Figure 8. Nomenclature used to define the phases of acceleration for a single repetition with a pause at the mid repetition point using illustrative data set.	60
Figure 9. An illustration of a acceleration profile of a continuous prone dumbbell row exercise repetition. P4 of the previous repetition combines with P1 of the current repetition. P2 and P3 blend without a pause at mid-repetition.....	61
Figure 10. A representative acceleration profile for one complete set of 10 repetitions for a trained subject.	62
Figure 11. Attenuation of the peak P4/P1 acceleration with different high-pass filter cutoffs.	65
Figure 12. Attenuation of the peak P4/P1 acceleration with different low pass filter cutoff frequencies.	65
Figure 13. Representative data showing the effect of high, low and band-pass filtering of acceleration data.	66
Figure 14. Average repetition duration (\pm SE) for each set for trained subjects.....	69
Figure 15. Average repetition duration (\pm SE) for each set for untrained subjects.....	69
Figure 16. Slope of peak-to-peak acceleration across repetitions for trained and untrained groups for each continuous set.	72
Figure 17. Mean peak acceleration for the trained group.	74
Figure 18. Plot of the peak-to-peak (PP) acceleration for each trained subject.	75
Figure 19. Mean peak acceleration for the untrained group.	76
Figure 20. Plot of the peak-to-peak (PP) accelerations for each untrained subject.....	77
Figure 21. Scatter plot of peak P4/P1 accelerations versus peak P2/P3 accelerations for the trained group.....	78
Figure 22. Scatter plot of peak P4/P1 accelerations versus peak P2/P3 accelerations in the untrained group.	78
Figure 23. Mean peak-to-peak (PP) acceleration magnitude for sets 1-4 for the trained group.	79
Figure 24. Mean peak-to-peak (PP) acceleration magnitude for sets 1-4 for the untrained group.	80
Figure 25. Peak accelerations for one subject performing a set of 4 repetitions in a 'maximal effort' manner.	103

LIST OF EQUATIONS

Equation 1. Instantaneous load about the elbow incurred during the execution of any upper limb exercise using a dumbbell	21
Equation 2. Calculation of resultant joint moment using only the moment of weight based upon joint angle.	24
Equation 3. The resultant joint moment about the elbow using the moment of the weight and moment due to acceleration.....	25

LIST OF TABLES

Table 1. Exercise volume including sets, repetitions, training frequency, and weight.	9
Table 2. Actual and predicted repetition maximum including intensity (% 100values.	32
Table 3. Repetition Maximum and weight prediction chart (Baechle, 1994)	32
Table 4. Protocol outline for sets and repetitions for 12 RM Testing.	53
Table 5. Protocol outline for sets and repetitions for Experiment.	54
Table 6. Subject characteristics. The standard deviation is shown in parentheses.....	68
Table 7. Paired t-tests of peak accelerations for P4/P1, P2/P3 and PP between repetition 1 and repetition 2 for each set.	71
Table 8. Paired T-tests of peak accelerations for P4/P1, P2/P3 and PP between repetition 1 and repetition 10 for each set.	71
Table 9 "Effective weight" calculations for a range of accelerations.	85

DEFINITIONS

Acceleration- Acceleration is the change in (derivative of) velocity as a function of time (m/s^2). (Enoka, 1994)

Concentric- The whole muscle length decreases and the muscle is activated. (Enoka, 1994).

Displacement- Displacement is a change in position measured in meters (m) (Enoka, 1994)

Eccentric- The whole muscle length increases while activated. (Enoka, 1994).

Exercise Intensity- Exercise intensity is a term used in strength training to describe the **relative effort** of an exercise. In resistance exercise, it is often expressed as a percentage of a maximum effort. This percentage is specific to the individual in question, as their maximum or 100% is specific to the individual. In free weight resistance exercise, intensity is commonly expressed as the percentage of the 1 repetition maximum or 1RM (Baechle, 1994; Zatsiorsky, 1995; Fleck & Kraemer, 1997).

Exercise Volume- Exercise programs are often quantified in terms of volume of training. In free weight resistance exercise, volume is commonly quantified as the number of sets multiplied by the number of repetitions multiplied by the weight (see Table 1). Note that the mechanical work is not computed by this calculation, since the weight is only a part of angular work. Total volume can be computed per exercise, per muscle group, per workout, per year, etc.

Table 1. Exercise volume including sets, repetitions, training frequency, and weight.

Exercise		Sets	Reps	Weight	Frequency	Phase length
Power Cleans		4	5	100	1 x week	3 weeks
Squats		4	10	100	2 x week	3 weeks
Bench Press		3	10	50	3 x week	3 weeks
Training volume						
	per Work out	4	10	100	1	= 4000 kg
(squats)	per week			4000	2	= 8000 kg
	per phase			8000	3	= 24000 kg
Whole workout						
	Power Cleans	4	5	100	1	= 2000 kg
	Squats	4	10	100	1	= 4000 kg
	Bench Press	3	10	50	1	= 1500 kg
						= 7500 kg
						per work out
Whole Phase						
	Power Cleans	4	5	100	x 1 x 3	6000 kg
	Squats	4	10	100	x 2 x 3	24000 kg
	Bench Press	3	10	50	x 3 x 3	13500 kg
						= 43500 kg
						per 3 weeks

Force- Force is defined as the mechanical interaction between an object and its surroundings. It is governed by Newton's second law, which states that Force (N) is proportional to the mass (kg) multiplied by the acceleration (m/s^2) (Enoka, 1994).

Isometric- (iso- same, metric - length) The whole muscle length does not change while being activated. The magnitude of the moment created by the weight or external force is equal to the moment generated by the muscles about the joint. (Enoka, 1994).

Isotonic Exercise - A term used in strength development literature to refer to the form of resistance training in which the weight is held constant. However, this does not indicate that the moment or resistance is constant through

the entire range of motion (Lieber, 1992; Howley & Franks, 1997). This term is used in weightlifting and in rehabilitation (Kisner & Colby, 1996). In muscle physiology literature isotonic means “same” (iso) “tension” (tonic). In human movement, the tension in a muscle changes throughout the range of motion due to changes in muscle length, muscle moment arms, contractile velocity, and acceleration even with a constant weight.

Kinetics – The study of forces and moments that are involved in the production of motion.

Load- The instantaneous moment generating requirements about each of the joints engaged in the exercise due primarily to the motion of the segments and the motion of attached weights (dumbbell, barbell, etc.) (Lieber, 1992; Komi, 1992). Moments are derived using Newtonian equations of motion where the sum of all moments acting on a system sum to equal the product of the moment of inertia and system acceleration.

Maximal Voluntary Contraction (MVC)- MVC or sometimes referred to maximal effort is defined as the maximal moment about a joint axis that a person can voluntarily exert for a given task in a given physiological state. This is not to be mistaken with maximal activation of the muscle.

Moment of the Weight – In a single joint system the moment of the weight is equal to the product of the weight and the perpendicular (\perp) distance from the line of action of the weight (vertically downward) to the joint axis of rotation.

Moment- (torque) The tendency of a force to produce rotation around an axis. Moment is equal to the product of force and the perpendicular (\perp) distance from the line of action of the force to the axis of rotation. This distance is called the moment arm. The unit of measure is the Newton-meter (Nm), (Komi, 1992).

Power - The rate of performing work (mechanical work) or the rate of transforming metabolic potential energy to work and or heat (metabolic power). Linear power is the product of force (N) and velocity (m/s) ($P = F \times v$). The unit of measure is the Watt (W) (Komi, 1992). Angular power is

defined as the product of moment (Nm) and angular velocity (radian/s) ($P = T \times \omega$).

Repetition- One complete cycle of a movement used as a form of exercise.

Repetition Maximum (1RM) - The maximum amount of weight the person can push, pull or hold for one repetition in a controlled manner. The RM weight is dependent upon the task.

Resultant Joint Moment (RJM)- The net rotational effect about a joint of all tissues spanning a joint including muscle, ligament, and bone. RJM is expressed in Nm.

Set- A group of repetitions performed consecutively without rest between repetitions (which may include a pause).

Strength- In resistance and free weight exercise, the ability to exert maximal effort on an object (external force) in an exercise, is commonly referred to as strength (Komi, 1992). Bandy & Lovelace-Chandler (1991) and Pardy, (1993) state that strength refers to the force output of a contracting muscle. In fact, force output is only a component of moment about a joint. A number of variables are involved in the production of resultant joint moment, muscle length, type of action (eccentric, concentric, isometric), velocity, range of motion, moment arm variation, etc. The strength of a muscle or muscle group must be defined as the maximal RJM generated under specific conditions (Knuttgen & Kraemer, 1987; Komi, 1992). Strength in human terms is related to the ability to generate and coordinate instantaneous joint moments about all joints involved.

Velocity- Velocity is the rate of change in position as a function of time. Angular velocity is measured in rad/s or deg/s. Linear velocity is measured in meters per second (m/s). (Enoka, 1994)

Weight- Weight is a special type of force where weight = mass x gravity (Enoka, 1994). Weight is reported in Newtons (N) as it is a force, although commonly but erroneously expressed in terms of mass (kg).

Weightlifting – One method of exercise that uses free weight (such as dumbbells and barbells) to form resistance during movement.

Work - Work is equal to the force (N) expressed through a displacement (m) with no limitation on time. The unit of measure is the Joule (J), (Komi, 1992).
Angular work is equal to the product of moment (Nm) multiplied by the angle (radians).

INTRODUCTION

Resistance training using free weights has become an integral component in the development of the neuromuscular system (NMS). Among the wide variety of devices available for developing the NMS, free weights resistance exercises are still commonly used in exercises for athletic training and rehabilitation. Progression in a free weight, resistance training exercise program commonly entails variation in the number of sets, repetitions, and load (Komi, 1992; Howley & Franks, 1997). Load is an important, if not critical component of resistance exercise because through its manipulation in the exercise program a coach, trainer, therapist or athlete/patient themselves can have control over the effectiveness of strength development and monitor the progression of their athletes or patients (Fleck & Kraemer, 1997; Zatsiorsky, 1995; Baechle, 1994). Understanding kinetics (the causal relationship among forces producing motion) is the key to understanding load. The kinetics of free weight resistance exercises has not been systematically examined in the literature. In the strength-training field the use of the term 'load' is often poorly or inconsistently defined.

A comprehensive definition of load is the instantaneous moment generating requirements about each of the joints engaged in the exercise arising from the demands placed upon the musculature from the moment of the free weight (e.g. dumbbell), the moment of the weight of the body segments (which act like weights) and acceleration dependent effects (Enoka 1994, Zatsiorsky 1995, and Komi, 1992). Practitioners and researchers have not accounted for the kinetics of resistance training (load variation). We must assume that they are unaware of these components, do not believe that these components are significant, or do not have the means to account for load variation due to kinetic differences. Often practitioners and researchers assume that given a fixed weight, the loading produced throughout the range of motion is the same from repetition to repetition (see for instance Harman, 1993). The limitations of assessing load by using weight as an estimate of load are unknown. Acceleration is the key kinematic parameter that accounts for variations in kinetics during

movement. Linear and angular acceleration is directly involved in the computation of moment about joints during free weight exercise. There are no studies that have examined acceleration during resistance training. This study is directed to furthering our understanding of load variation in free weight resistance training by measurements of dumbbell acceleration.

LITERATURE REVIEW

This review of literature will be used to examine key principles and concepts related to load, its assessment, and application in free weight resistance exercise. We will begin with a brief overview of resistance exercise to provide a contextual background for this study.

Resistance Exercise

Methods

There are a variety of resistance training methods that are used in the development of neuromuscular strength. The various methods of NMS development are manual resistance, constant resistance, variable resistance, and accommodating resistance.

In the manual resistance method, a training partner applies the resistance by pushing, pulling or holding one or more body segments. In this case, the resistance applied by the partner can be represented by force acting on the segment. This force acts about the joint axis of rotation to produce a resistive moment that must be overcome along with the moment of segment weight and acceleration dependent moment by the resultant joint moment. Hand held dynamometers work on the basis of holding an implement (force transducer) as tightly as possible to the test subject segment, giving a measurement of force but not resultant joint moment.

“Constant resistance” is the most common form of resistance used in exercise (Howley & Franks, 1997). Free weights and stack machines are the most frequent forms of this type of resistance training. In “constant resistance” exercise the weight does not change throughout the ROM even though the load (RJM) does. A better term may be constant weight resistance exercise. However, contrary to what the name implies the forces exerted by the muscles are anything but constant throughout the ROM, and as such the RJM, also varies throughout

the ROM. Even from a perceptual point of view, most people clearly identify that the load is anything but constant during “constant resistance” exercise.

Variable resistance is a resistance that is changed throughout the ROM (Lieber, 1992), typically through the use of a cam or variable lever or moment arm. Accommodating resistance is created by the use of computer-controlled machines with hydraulic or electric motors that control the speed of the motion allowing the development of maximal effort contractions through the range of motion.

Load

The segments of the human body do not move in linear motions but rather in a rotary manner about joint axes of rotation. Purposeful human movement requires segmental rotation, which results from the balance among moments produced by internal and external forces. The external forces are associated with external loads arising from a weight attached to a body segment, a force applied by a machine, or a force created by an elastic attached to the body. The internal forces primarily arise from muscle under direct control of the nervous system. Internally, the tendency of tissue force (forces from ligaments, muscles and bones) to cause rotation is called resultant joint moment (RJM). RJM arising primarily from muscle activation are used to produce or control angular movement (Lieber, 1992). All purposeful human motion arises from the production of RJM about each of the joints. The coordination of the resultant joint moments allows humans to move and interact with their environment by applying forces to the external world (Lieber, 1992).

It is important to make the distinction between internal load and external load in relation to the human body. Internal loads are the loads or forces created within the tissues of the body (muscular, skeletal, and connective tissues). This internal load is critical to understand as it influences the development of the neural, muscular and skeletal systems. Internal load is different from the external loads, which is often the parameter estimated in exercise science. The external load is related to the force that the human body can effect upon or against the

external world (i.e. a mechanical device, a bar, a dynamometer, a ball, the ground, etc). In the scientific study of exercise we often measure external forces, as estimates of internal load. The best non-invasive method for assessing internal load is by computation of the instantaneous moment (resultant joint moment) generating requirements about each of the joints engaged in the exercise due to the motion of the weight and segments (Lieber, 1992; Komi, 1992). The resultant joint moment represents the net rotary tendency of all forces spanning a joint. The computation of RJM requires that the motion (instantaneous kinematics) of the body segments be measured throughout the range of motion of the exercise. During resistance training, motion is partially controlled by limiting and or standardizing the range of motion allowing derivation of average speed or cadence. However, this limited motion control does not permit direct computation of resultant joint moment. In some cases, stipulation of the average cadence of motion has been used, but no studies to date have examined the instantaneous kinematics within a repetition or free weight exercise

The term constant resistance is used in strength and conditioning literature to refer to this form of resistance training in which the weight is held constant. However, as we will see this does not indicate that the RJM is constant through the entire range of motion. In work by Hay, Andrews & Vaughan (1980), it was observed that as loads increased from 40 to 80% of the 4 RM load, that kinematics of the movement were altered. It was reported that the subjects were flexing more at the hips during the squat, which caused the resultant muscle force to increase disproportionately to the load. In other words, the basic exercise was altered with different weights used, which would necessarily involve a change in acceleration.

The prescription and assessment of load is an important component in developing and monitoring free weight training exercise (MacDougall, Wenger, & Green, 1991). For a comprehensive assessment of load the RJM of each joint needs to be derived for all instances of each repetitions of the exercise, but this is not currently practical. As such, it is important to understand the limitation(s) of

using weight as a load estimate. This has important implications in the development of programs used to enhance athletic performance, and physical rehabilitation. The development of the NMS may be ineffective if the load is not high enough to provide adequate stress to the system. If the loads are too high, and therefore overstress the system, then injury or compensatory movement may occur (i.e. a change in the NMS mechanics due to a change in neural recruitment strategy, recruiting different muscles, a greater number of muscles, or different motor units within the involved muscles). Further, information about the limitations of using weight as an assessment of load may be useful in the interpretation of previous studies that have not accounted for this possible variable. This would apply to a number of exercise dose/response studies (for instance, Bompa, 1996; Dudley, Tesch, Miller, & Buchanan, 1991, Hortobagyi, Katch, & LaChance, 1991; Reiser, Smith, & Rattan, 1996; Stone & Borden, 1997; Enoka, 1994; Young, Jenner, & Griffiths, 1998). Fleck and Kraemer (1997) have identified a high level of variability in several of these studies. This variability could be partially attributed to differences in acceleration profiles between individuals, repetitions, and between training sessions.

As a result of assessing load as the weight of the dumbbell, practitioners often believe that when they prescribe an exercise in terms of sets and repetitions, the individual is performing each set and repetition with the same load throughout the ROM. Thus adjustments made to training programs are often based on this assumption. This does not take into account any variation in acceleration among other variables (such as, orientation angles of segments, position of segments, compensatory motion, etc.), which may change the actual resultant joint moment being generated or required. Although a clear relationship between acceleration and the number of sets and or repetitions has yet to be established, a clear mathematical relationship does exist between acceleration and the instantaneous load during a free weight exercises. See section termed "Mathematical Model of Free Weight Exercise".

Moment Arm

Each muscle spanning a joint will have a moment arm, which will vary with the joint angle. The moment arm is the perpendicular distance from the line of action of the muscle to the instantaneous joint axis of rotation (Adrian & Miller, 1998). The amount of neural activation of a muscle will influence the force generated by the muscle. The force produced by the muscle will create a rotary tendency about the joint via the moment arm (recall that moment is the product of force and the moment arm). Thus moment arm variations with joint angle and potentially by neural activation strategy will influence the magnitude of moment that can be generated by a muscle. The biceps brachii and its action about the elbow joint will be used as an illustration. The moment generating ability of the biceps brachii about the elbow is based upon the product of muscle force and moment arm. The upper limits of muscle force production are dictated by the force/length and force/velocity relationships. The actual force produced is dependent upon the neural activation level. In order for the biceps to contribute to elbow flexion in a standing position, the muscle must generate a moment adequate to overcome the 1) the moment of weight of the forearm and hand, 2) the moment produced by elbow extensor muscles and 3) any external moment produced by attached devices or weights. As the elbow flexes the moment arm of the biceps brachii muscle force changes, the length/tension relationship changes, and the velocity changes. Further, since biceps brachii is a biarticular muscle (a muscle that spans two joints), the motion about the shoulder will also influence force generation and hence moment about the elbow. Muscle moment arm variations are an important internal factor which influences muscle force generation requirements during human motion.

Moment of Weight

The moment of the weight of a dumbbell, barbell, and segment weights changes throughout the range of motion because as the segments change in angular position about the joint, the magnitude of the moment arms of the weights about the joint also change, even though the weight remains constant.

When compared to the moment of segment weight, the moment of the weight of the dumbbell or barbell is normally the greatest component contributing to the load. This is true for two reasons: 1) the weight of the dumbbell or barbell are normally greater than segment weights for upper body resistance training and 2) the moment arms for body segments are normally smaller than free weights since the barbells and dumbbells are normally attached distally. For example, considering mass (weight) alone, if the mass of the dumbbell used in biceps curls was 15 kg and the mass of the body segments (forearm and hand) was approximately 4 kg, the majority of the mass would arise from the free weight. Also, the centre of mass of the forearm and hand would be substantially closer to the elbow (small moment arm) in comparison to the centre of mass of the dumbbell located in the hand. As such, both the larger magnitude of the weight and the larger size of the moment arm of free weights result in their greater contribution to external loads than segment weights in individuals with normal strength levels..

Resultant Joint Moment

Load has been defined as the instantaneous moment generating requirements about each of the joints engaged in the exercise due primarily to the motion of the weight and segments (Lieber, 1992; Komi, 1992). For a single segment motion, resultant joint moment and the moment of weight of the body segments and dumbbell, sum to equal the product of the moment of inertia and the angular acceleration based upon the Newtonian equation of motion ($\Sigma M_E = I\alpha$).

Examination of the Newtonian equations of motion reveals that three components are essential to understand in a complete description of load;

- 1) Resultant joint moment
- 2) Moment of weight, and
- 3) Acceleration dependent moment

Instantaneous RJM is the calculation of moment at any one particular instant in time of an exercise; it is both joint angle and acceleration specific. It is

important to recall that RJM arises from the net rotary tendency of all the tissues spanning a joint including both agonist and antagonist muscle activity. Equation 1 shows the various components that contribute to the instantaneous RJM in a free weight resistance exercise during a prone dumbbell row. Even though the segment weight and dumbbell weight remain constant, the RJM would need to be computed at each instant of the movement due to the fact that; 1) the acceleration is changing and 2) the moment arms of weight are changing about each of the joints. A complete description of the variation in RJM throughout the motion, including both the lifting and lowering phases, would be necessary for a comprehensive depiction of the “loading profile” of the exercise. Since this exercise is multi-segmental, where there is segmental rotation about the elbow and shoulder, both the shoulder RJM and the elbow RJM would need to be determined.

Equation 1. Instantaneous load about the elbow incurred during the execution of any upper limb exercise using a dumbbell .

The following equation reflects the summation of moments involved in the motion. The resultant joint moment can be calculated for each joint and each instant of an exercise using standard Newtonian equations of motion. Load is then calculated as the resultant joint moment(s) used to produce a moment.

$$RJM_{elbow} = I\alpha - M_{WFA} - M_{WH} - M_{DB}$$

Where:

RJM_{elbow} = Resultant joint moment about the elbow

I = Moment of inertia

α = Angular acceleration

M_{WFA} = Moment of the weight of the forearm

M_{WH} = Moment of the weight of the hand

M_{DB} = Moment of weight of the dumbbell

It is interesting that studies have not examined the kinetics (RJM computation) involved in free weight exercises, especially the influence of

acceleration on load. This may have arisen due to the fact that research in exercise science has largely been discipline specific. In other words, an interdisciplinary approach is necessary to understand resistance exercise including both biomechanics and exercise physiology.

Dynamometry

Dynamometers have been the gold standard in regards to strength assessment (Perrin, 1954). They are used for research in the medical and rehabilitation fields and for treatment in rehabilitation and high performance athletics. The cost of these machines is somewhat prohibitive for the use in public gyms. The motion of these machines is accomplished by computer control of hydraulic or electric motors with position and velocity feedback. This system provides accommodating resistance. A load is generated that is equal in magnitude to but opposite in direction to the RJM (moment of force) exerted by the subject (Enoka, 1994). Dynamometers are considered to be “isokinetic” or isovelocity machines since the angular velocity of the displaced body segment is constant for the majority of the movement. This also leads to a few of the problems associated with using the dynamometer.

Many researchers have used dynamometers to quantify moment, work, and power output of muscle (Enoka, 1994). Winter, Wells and Orr (1981) have shown acceleration errors in the calculation of RJM can be substantial, particularly at higher speeds. Some of these errors can be compensated for by appropriate calculations (Gransberg & Knutsson, 1983). Acceleration errors in calculating RJM during computer controlled “isokinetic exercise” have been important to consider. Interestingly, the community of dynamometry users has attempted to address the issue of acceleration and its contribution to RJM even though acceleration errors are minimized due to the isovelocity condition.

Ironically the use of dynamometers may have added to our oversight in quantification of load in resistance training. Dynamometers have been used for many years in formulating what we know about the development of NMS by providing accurate quantification of strength about a joint. The main strength and

possible fault of dynamometry was that, in its creation the inventors “eliminated” the acceleration component of the moment by providing a constant velocity through the majority of the ROM (with the exception of the beginning and the ends of the ROM). This is the operational basis of dynamometers, in which a situation of static equilibrium is created so that measured resultant joint moments are not influenced by acceleration, ideally. Thus, researchers and practitioners may have inadvertently lost sight of the key components of load during “regular” resistance exercises that are clearly elaborated in the basic Newtonian equations of motion. The knowledge of acceleration profiles (variation in acceleration during motion) in strength training exercise may have important implications for future research and practice. Indeed, an understanding of acceleration may permit us to examine the results of previous exercise dose/response studies in a different light.

Mathematical Model of Free Weight Exercise

To help understand the relationship that acceleration has with load, as dictated by Newtonian Equations of Motion, we will examine the loading during a movement arising from two sources; 1) the moment of weight and 2) the moment arising from acceleration. We have chosen the bicep dumbbell curl and will examine the parameters that affect load during this “simple”, single joint movement. Calculation of RJM about the elbow is performed for every instance of the movement (at arbitrary time increments). Two cases will be shown. In Case 1 (corresponding to Equation 2), the elbow RJM will be derived based upon the moments of the weight of the dumbbell and the segments. In Case 2, (corresponding to Equation 3) the elbow RJM will be derived using both the moment of weight of the dumbbell and segments, and the moment due to the angular acceleration. For illustration purposes, the calculations will only be shown for the 90° elbow joint angle. This point in the movement was selected since the forearm is parallel to the floor (horizontal). In this position, the moment of weights is at its maximum value. Our model is based on the well-known Newtonian equation of motion as described in the previous section:

$RJM_{\text{joint}} + \text{moment of the weight of the segments} + \text{the moment of the weight (dumbbell)} = I\alpha$

In the following example the weight of a 10 lb. dumbbell would be -44.5 N ($4.545 \text{ kg} \times -9.8 \text{ m/s}^2 = -44.5 \text{ N}$). In the calculation of the moment for each body segment the body segment parameters (Robertson, 1997) were used to estimate the weight of each body segment based upon total body weight. A body mass of 80 kg (-784 N body weight) was used.

Equation 2. Calculation of resultant joint moment using only the moment of weight based upon joint angle.

$$\begin{aligned} RJM_E + (W_{FA} \times d_1) + (W_H \times d_2) + (W_{DB} \times d_3) &= I\alpha \\ RJM_E + (0.016 \times 784 \text{ N} \times d_1) + (0.006 \times 784 \text{ N} \times d_2) + (44.5 \text{ N} \times d_3) &= I\alpha \\ RJM_E + (0.022 \times 748 \times d_4) + (44.5 \text{ N} \times d_3) &= I\alpha \\ RJM_E + (0.022 \times 748 \times 0.37 \text{ m}) + (44.5 \text{ N} \times 0.25 \text{ m}) &= I\alpha \\ RJM_E + (17.24 \times 0.25 \text{ m}) + (44.5 \text{ N} \times 0.33 \text{ m}) &= I\alpha \\ RJM_E + (4.31 \text{ Nm}) + (14.68 \text{ Nm}) &= I\alpha \\ RJM_E + 18.995 \text{ Nm} &= I\alpha \end{aligned}$$

The moment of weight of the forearm, hand and dumbbell are listed above. We will set the acceleration equal to zero, so that the RJM_E represents the moment needed to overcome the moment of weight alone.

$$RJM_E = -18.995$$

Where,

I = Moment of inertia (kgm^2)

m = Mass (kg)

α = Angular acceleration

d_x = The distance is the moment arm which is from the axis of rotation of the joint to the centre of mass of each segment or dumbbell

RJM_E = Resultant joint moment of the elbow

d_1 = moment arm from centre of mass of dumbbell to elbow joint

d_2 = moment arm from centre of mass of forearm and hand to elbow joint = 0.25 m

d_3 = centre of mass of DB = 0.33 m

Equation 3. The resultant joint moment about the elbow using the moment of the weight and moment due to acceleration.

$$\begin{aligned}
 I &= mr^2 \\
 I &= 4.54 \text{ N} \times 0.33^2 \text{ m} \\
 I &= 4.54 \text{ N} \times 0.1089 \text{ m} \\
 I &= 0.494 \text{ kgm}^2 \\
 I\alpha &= 0.494 \text{ kgm}^2 \times 69.8 \text{ rad/s}^2 \\
 I\alpha &= 34.48 \text{ Nm}
 \end{aligned}$$

r = The radius from the axis of rotation of the joint to the centre of mass of the dumbbell

We use a peak angular acceleration of $-4000^0/\text{s}^2$, which was measured by placing an accelerometer on a dynamometer as an estimate the accelerations of the segment during normal motion. This estimation is then converted to SI units (rad/s^2) = $-4000 / 57.3^0 \text{ rad} = -69.8 \text{ rad/s}^2$. The moment of inertia of the dumbbell alone (ignoring body segments) about the elbow joint was estimated to be .

$$\begin{aligned}
 \text{RJM}_E + \text{Moment of weight of dumbbell, forearm and hand} &= I\alpha \\
 \text{RJM}_E + 18.995 &= 34.48
 \end{aligned}$$

$$\begin{aligned}
 \text{RJM}_E + 4.31 \text{ Nm} + 14.68 \text{ Nm} &= I\alpha \\
 \text{RJM}_E + 4.31 \text{ Nm} + 14.68 \text{ Nm} &= 34.48 \text{ Nm} \\
 \text{RJM}_E &= -34.48 \text{ Nm} - 18.995 \text{ Nm}
 \end{aligned}$$

$$\text{RJM}_E = \underline{-53.47 \text{ Nm}}$$

I = Moment of inertia (kgm^2)

m = Mass (kg)

α = Angular acceleration

RJM_E = Resultant joint moment of the elbow

In Case 2, when we consider both the moment of weight and the relatively high acceleration value used in this case, the $\text{RJM}_{\text{ELBOW}}$ is -53.47 . This is 2.8 times that of $\text{RJM}_{\text{elbow}}$ computed based upon the moment of weight alone.

The RJM data is shown graphically (Figure 1) for the entire movement at 10° increments for lower recorded acceleration values. The graphical representation of the calculations of $\text{RJM}_{\text{ELBOW}}$ (for the biceps curl for the ascent phase of the repetition for 0.0 to 140.0 degrees. The $\text{RJM}_{\text{ELBOW}}$ curve (diamond

symbols) is illustrated for Case 1 where the moment of the weight of the dumbbell and the body segments are considered. For Case 2, the resultant joint moment curve (square symbols) was calculated using Newton's equation of motion with an acceleration component.

One can clearly see the impact of acceleration on the magnitude and timing of the RJM. This model further points to the importance of acceleration in the assessment of load.

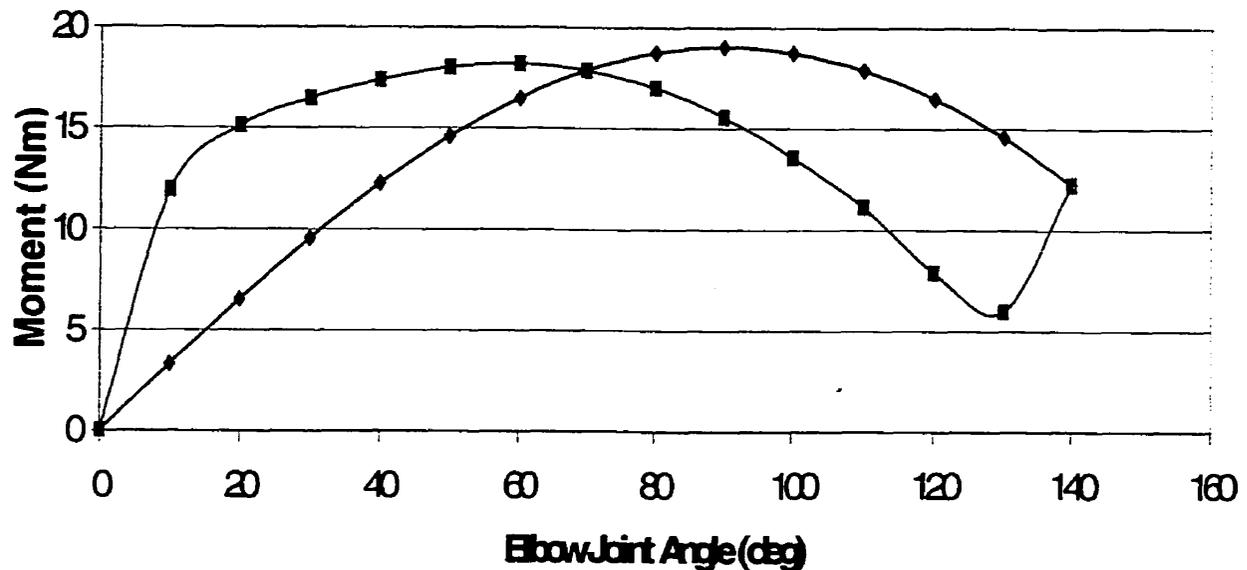


Figure 1. RJM_{ELBOW} during the ascent phase of a biceps curl. The RJM_{ELBOW} (diamond symbols) is shown which was derived solely from the moment of the weight of the dumbbell and the body segments. RJM_{ELBOW} (square symbols) is determined using both moment of weight and acceleration.

Maximal Voluntary Contraction (MVC)

The MVC can be defined as the maximal amount of force that a person exerts for a given task in a given physiological and psychological state. This is commonly used in research when assessing strength and often is applied to isometric contractions (Fleck & Schutt, 1985). The level of motivation of the subject influences force production. This makes MVC a state dependent measurement. Therefore MVC should not be exchanged with a measurement of maximal activation of the muscle. This motivational effect will influence all

assessments of NMS (e.g. 1RM test, dynamometry or other). The motivation within a repetition and between repetitions has not been evaluated but would certainly influence the neural activation of muscle resulting in fluctuation in force levels. The variations in force would manifest themselves in acceleration differences between repetitions.

Assessment of Load

The end result of force generation by the human body on an external object (ground, dumbbell, etc) relates to a number of integrated factors. One must take into account not only biomechanical, neurological, and genetic factors, but also factors like motivation (Knuttgen & Kraemer, 1987; Komi, 1992). When an individual lifts a heavier dumbbell, the RJM will increase in direct relation to the increase in load if and only if the kinematics of the movement remains the same (Enoka, 1994). Further to this, the load assessment must account for the basic physical characteristics of load in which load is influenced by the moment of weight and acceleration (Komi, 1992). In the development of NMS the ability to create RJM under maximal voluntary conditions (MVC) is commonly referred to as strength (Komi, 1992; Fleck & Kraemer, 1997). This simple definition has been adopted not only in the pursuit of athletic development but also by therapists and other practitioners.

In the assessment of strength many practitioners have defined load as the weight being lifted or controlled in the exercise through the complete ROM. Weight is simply defined as the product of mass and gravitational acceleration ($1g = 9.8 \text{ m/s}^2$). In the case of free weight resistance exercise it is a reasonable assumption that the acceleration due to gravity is constant (-9.8 m/s^2). However, even though the gravitational acceleration is constant, the segmental and free weight acceleration through the movement will not be constant.

The definition of load is a difficult concept not only in weight lifting but in the understanding of NMS development, and is often oversimplified. There have been no explanations of how various training parameters effect the development of strength. There are general concepts of what types of programs develop

strength vs. strength endurance for example, but none have been definitive (Fleck and Kraemer, 1997). Among other contributing factors, this may be due to the lack of awareness of variation in acceleration through the ROM and the influence on instantaneous loading.

As stated previously, the most comprehensive definition of load is the instantaneous moment generating requirements about each of the joints engaged in the exercise arising from the moment of the weight (dumbbell), the moment of the body segments (which act like weights) and acceleration dependent effects. This requires that the RJM about each of the required joints at each instant of the ROM be measured (Komi 1992, and Enoka, 1994). Comprehensive depiction of RJM is necessary to interpret the loads or forces on the tissues of the body (muscle, tendon, ligaments, bone, etc) that may adapt to this specific stimulus. Currently, load is thought of as a static parameter which can be assessed by the weight employed during free weight exercise. In scientific study of exercise RJM is our best estimate of load imposed upon the body tissues. Until recently the means to measure the exact forces on the bones, ligaments, muscles and tendons during motion has not been available. Recent use of buckle transducers (Mendelson, Peckham, Freehafer, & Keith, 1988) and optical fiber sensing systems (Tyska, Dupuis, Guilford, Patlak, Waller, Trybus, Warshaw, & Lowey, 1999) are beginning to allow us to measure some of these many tissue forces, in vivo. Even though RJM is our best load measure, the measurement requires expensive and time-consuming technology, such as video motion analysis systems.

Some well-known strength and conditioning coaches like Louie Simmons (a well respected coach in power lifting, see <http://www.westside-barbell.com>) employ many training techniques to both maximize acceleration and compensate for acceleration in their programs. While they have not yet clearly explained why they use these techniques, they have shown some very impressive results. The training methodology clearly emphasizes acceleration.

We will briefly explore a variety of means that have been used to estimate or assess load including dynamometers and weight methods (RM). We will also examine a more recent means of kinetic assessment called the accelerometer.

Weight

As the fields of Exercise Physiology and Biomechanics have evolved so to have the definitions and understanding of load in free weight resistance training. Many practitioners, therapists and researchers have employed the basic definition of load that states load is the weight used in exercise. This definition can be seen back in the early studies of Delorme (1945). More recently, we have seen definitions that attempt to integrate the movement parameters of the exercise into the evaluation. Fleck and Kraemer (1997) use a definition called Dynamic Constant External Resistance. They argue that this definition accounts for load variation due to mechanical advantage of the joints [moment arm variations] involved in the motion and the length of the muscle at a particular point of the movement. Although this definition is more encompassing it still does not account for acceleration and deceleration of the movement and further has not been adopted by the mainstream. More recently, we see the use of a term called isoinertial exercise (Abermthy, Jurimae, 1996; Wilson 1993; Murphy, Wilson & Prior, 1994; Viitasalo & Amo 1984). Isoinertial implies constant resistance to motion rather than merely a constant resistance or load through the ROM (Abermthy, 1996). Again, the base definition may not be entirely accurate, due to the assumption that the resistance to the motion is constant.

Repetition Maximum

Many of the theories regarding the assessment and prescription of exercise have stemmed from work by DeLorme (1945). The basic test in DeLorme's model involves the determination of the number of repetitions that a person can perform to exhaustion in lifting a certain mass. Many authors now describe this mass (kg) in terms of a 'repetition maximum' or RM. (Komi, 1992). Prescriptions of resistance training programs often use a percentage value.

Calculating the appropriate percentage of the subjects' maximum strength at a 1 RM (i.e. the maximum weight that a person can use to complete the required exercise) derives the percentage.

The most commonly seen definition and assessment method of load in free weight resistance exercise is the Repetition Maximum (RM) (Baechle, 1994). The RM method defines the load as the maximum amount of weight that can be moved through a full range of motion given proper weight lifting technique for a given number of repetitions. The RM may be a 1 RM assessment or multiple RM's. In free weight resistance exercise prescribed loads are often assigned as a percentage of a 1RM (the 1RM weight would be 100%). This percentage of load is often called exercise intensity (Fleck & Kraemer, 1997; Zatsiorsky, 1995; Baechle, 1994; Young et, al., 1998). This methodology was based upon the work of DeLorme in the 1940s (Enoka, 1994; Komi, 1992).

The test-retest reliability of the 1RM for experienced lifters is $r = 0.92$ to 0.98 (Sale, 1991; Hortobagyi, Katch, & LaChance, 1989; Hennessy & Watson, 1994; Hoeger, Hopkins, & Barette, 1990; Abemethy, Wilson, Logan, 1995). In the case of more dynamic activities (weighted squat jump) the interclass reliability is lower $r=0.86 - 0.96$ (Viitasalo 1985a; and 1985b). Their study also found that as the load increased the coefficient variation also increased.

This 1RM value is then considered the 100% value and load prescriptions in exercise programs are assigned as a relative percentage of this value. From the example below (table 2), a person who has a measured 1RM of 100 lbs would have a predicted 81% load of 81 lbs. We can also see from the example that there is also an estimated value of a 7RM load for this value (i.e. an estimation that this weight (81lbs) could be lifted a maximum of 7 times). This value is derived from a chart (See table 3) which has been derived from an algorithmic equation that converts RM values to weight values (in this case lbs.). These charts are useful because of the increased difficulty and unfamiliarity of lifting heavy weights for many people (Logan, Fornasiero, Abemethy, & Lynch, 2000). Many RM tests are performed at higher repetitions, like a 10 RM, for this reason. There have been several such equations established (Brzycki 1993;

Lander 1985; and Mayhew, Ball, and Bowen, 1992), which have shown a high level of correlation ($r = 0.89 - 0.96$) between the predicted and the actual 1RM values. These equations are based upon the assumption that the number of repetitions completed at a given percentage of 1 RM does not change with training. This assumption appears to be true for some lifts (bench and leg press) but not others (Hoeger et al., 1990). It has also been observed that as the number of repetitions increase in the relationship so does the variability (Logan et al., 2000). Mayhew et al. (1992) has shown that some formulas (Brzycki 1993, Lander 1985) over-predict by 1.5 - 2.5 kg.

In strength training, an increase in load may alter the kinematics of a movement (Zatsiorsky, 1995). With this knowledge, some authors recommend intensities for strength training of 4-6RM with 3-6 sets of each exercise. (Atha, 1981; Fleck & Kraemer, 1997; Mcdonagh & Davies, 1984; Sale & MacDugall, 1981). Mcdonagh and Davies (1984), also reported that in untrained subject's, torque requirements of less than 66% do not increase strength. Exercises with requirements above 66% of 1RM have been found to increase strength 0.5 to 1.0% after each training session. Harre (1982) suggests 60-80% of 1 RM for beginners with 8-10 repetitions in each set. For elite individuals the range is increased to 80-100% of 1RM with 2-5 repetitions per set.

With these methods of load assessment and exercise prescription, a large variability in loading is possible (even without consideration of acceleration). For instance, if 100% or 1RM were to equal 100 kg barbell mass, the working range of training volume for 3 sets of 2-5 repetitions at 80% would be 480 kg (80 kg for 2 reps x 3 sets) to 1200 kg (80 kg for 5 reps x 3 sets) per training session. This very large range of load assessment values does not consider changes in acceleration.

Table 2. Actual and predicted repetition maximum including intensity (% 100 values).

	Intensity	# Repetition Maximum	Weight (lbs)
Actual 1 Repetition Maximum	100%	1RM	100 lbs
Predicted Values	81%	7RM	81lbs

Table 3. Repetition Maximum and weight prediction chart (Baechle, 1994)

%/1RM	100%	93.5%	91.0%	88.5%	86.0%	83.5%	81.0%	78.5%	76.0%	73.5%
# of Repetitions	1	2	3	4	5	6	7	8	9	10
Weight (lbs.)	5	5	5	4	4	4	4	4	4	4
	10	9	9	9	9	8	8	8	8	7
	15	14	14	13	13	13	12	12	11	11
	20	19	18	18	17	17	16	16	15	15
	25	23	23	22	22	21	20	20	19	18
	30	28	27	27	26	25	24	24	23	22
	35	33	32	31	30	30	28	28	27	26
	40	37	36	35	34	33	32	31	30	29
	45	42	41	40	39	38	37	35	34	33
	50	47	46	44	43	42	41	39	38	37
	55	51	50	49	47	46	45	43	42	40
	60	56	55	53	52	50	49	47	46	44
	65	61	60	58	56	54	53	51	49	48
	70	66	64	62	60	59	57	55	53	52
	75	70	68	66	64	63	61	59	57	55
	80	75	73	71	69	67	65	63	61	59
	85	80	77	75	73	71	69	67	65	63
	90	84	82	80	77	75	73	71	68	66
	95	89	87	84	82	80	77	75	72	70
	100	94	91	89	86	84	81	79	76	74

There is often speculation that testing strength at 1RM may also be affected by several acute variables, such as preloading and recovery between efforts (Abemethy et al. 1995). Research has shown performances to be enhanced with isometric preloading and plyometric activity (Wilson, Lyttle, Ostrowski, & Murphy, 1995; Tihanyi, Apor, & Fekete, 1982). Another common belief is that recovery between efforts may have negative implications upon 1RM

tests. This was refuted by Anderson & Kearny (1983) who reported that 60% of novice study participants required only 4 sets to find 1RM, and all participants had achieved 1RM by the 6th trial. Further Weir, Wagner, and Housh (1994) showed that 1RM trials were not compromised when rest was 1, 3, 5, or 10 minutes in duration. Sewall and Lander (1991) went on to show that there were no differences when trials were separated by 2, 6, and 24 hr periods.

Even though the maximal effort RM test can be used to reliably determine a 1RM weight in controlled settings, this does not mean that the exercise intensity is a constant due to factors such as acceleration

Accelerometry

There are several motion-sensing technologies that have been used for many years. Three such technologies: infrared, radar, and video are all externally referenced systems. As a result they are subject to occlusions and numerous interference's and noise sources. Inertial sensors attach directly to the object or body being measured and give an output signal proportional to its own motion with respect to an inertial frame of reference (Verplaetse, 1996). The two types of inertial sensors are the accelerometer and the gyroscope. Our discussion will focus on the accelerometer (see Figure 5), as it is the technology of interest for our study.

Accelerometers sense translation acceleration and are valuable to the study of movement because they function regardless of external references. Accelerometers have also been in use for several decades in the transportation industry but until more recently the cost and size have kept its use to spacecraft, airplanes and submarines.

Accelerometer signals can be integrated once with respect to time to attain velocity and integrated twice to get position. The signal can also be differentiated to obtain the mechanical parameter, jerk (rate of change of acceleration).

There are three accelerometer technologies used including piezoelectric, piezoresistive and capacitive. Almost all accelerometers regardless of the base

technology are of a pendulous type, which has a known mass that is mechanically coupled to the rest of the sensor. This mass is called the 'proof mass'. When the sensor is accelerated this 'proof mass' tends to stay at rest. The relative motion between the proof mass and the other components of the sensor are detected as an inertial force and this motion is translated into a voltage signal.

The accelerometer most commonly used in the study of human motion is a piezoelectric model. There is a piezoelectric film on the beam of the cantilever, which has the proof mass on the end. When the system is accelerated the proof mass causes the beam to deflect. This in turn stretches the piezoelectric film on one side of the beam to stretch and to shorten on the other side of the cantilever creating a voltage signal proportional to the deflection of the beam.

Accelerometers come in different shapes and sizes and measures positive and negative acceleration in m/s^2 or expressed in 'g' values (multiples of gravitational acceleration, where $1\text{g} = -9.8 \text{ m/s}^2$). The simplest model is a linear uni-axial model, which measures positive and negative values of acceleration in one plane. There are also bi-axial and tri-axial accelerometers, which measure acceleration through two or three planes, respectively. The main advantages of accelerometers over the video analysis methods are an enhanced sampling rate (60 Hz for video versus hundreds of Hz for the accelerometer), the ability to measure very small movements (resolution of the accelerometer is so high that it can sense vibration of a surface in response to speaking), and its ease of use and application.

Accelerometry for Assessment of Human Motion

Accelerometry is the study of the acceleration of an object or human body segment. Acceleration has been traditionally measured using video motion analysis, but accelerometers have recently been introduced into the realm of human motion analysis. Accelerometers are being used in a variety of areas of human motion analysis, such as the study of tremor (Gallasch & Kenner, 1997), physical activity or energy consumption (Chen & Sun, 1997), neurological

disorders (Ng & Kent-Braun, 1997), and motor control (Baratta, Solomonow, Best, D'Ambrosia, 1997). More recently Herren, Sparti, Aminian, and Schutz (1999) studied the ability to evaluate speed and incline in running using accelerometry. The accelerometer has not yet been used in the study of RJM production or loading during resistance exercise.

Zedka and Prochazka (1997) studied the effect of hand waving on the accelerations in the low back. This study showed the ability of the accelerometer to measure very small levels of acceleration ($\pm 1 \text{ m/s}^2 = 1/10$ of a 'g'). The acceleration profiles shown in this study show the repetitive or cyclical nature of movements based upon acceleration data. Further, they illustrate acceleration dependent EMG activity in the back musculature.

The most germane study related to this project is that of Thompson and Bemben (1998) who used the accelerometer to evaluate the reliability and accuracy of the accelerometer as a measure of muscular power. The method used was to have subjects attempt their 1RM bench press (BP) on a 'linear' BP apparatus (Smith Machine). The average power, average velocity and total displacement were measured using three different methods. The three methods were 1) a uniaxial piezoresistive accelerometer (ICS Sensors Model 3145), 2) video motion analysis (VMA) using the Peak 5 system, and 3) a photoelectric timer system (photoelectric cells separated by 20 cm). Measurements were made for a 20 cm range motion of the barbell, as well as over the whole ROM. Instantaneous calculations were not performed. Acceleration data was collected at a rate of 60 Hz. This selected rate of collection is identical to that of the video motion analysis system used which measures positional data (Peak5 Video Analysis system at a rate of 60 frames·s⁻¹). The accelerometer data was integrated to give velocity and then again to give displacement. This displacement data was then summed to give total displacement. External force acting on the barbell was calculated by using the accelerometer data, which combined the acceleration due to gravity and non-gravitational acceleration. The combined acceleration was then multiplied by the mass, and expressed in force

units, termed “the effective weight”. The linear power (W) was calculated by multiplying velocity (m/s) by force (N).

These values for power and displacement were then compared against measurements using video motion analysis and photoelectric cell techniques. Repeated measures ANOVA tests determined that trials could be collapsed for all variables. In order to make a comparison to the photo-electric cell method a 20 cm segment had to be examined from all techniques. In this measurement the film analysis yielded a mean average power of $356.6 (\pm 94.8)$ W. This value was found to be significantly greater ($p \leq 0.05$) than both the accelerometer average power (335.5 ± 97.7 W) and photocell mean average power (342.0 ± 97.2 W). Pearson correlation coefficients between the three methods were all significant ($p \leq 0.05$), with the lowest correlation being $r = 0.93$. The study found that accelerometry showed slightly larger amounts of variation (29.1%) as compared to video analysis and photocell (276.6% and 28.4% respectively). This would be expected, as the accelerometer data is not smoothed and represented the actual trial-to-trial variation in motion. The other methods averaged the motion, and averaging has the well-known result of decreasing variation. Thompson and Bembem (1998) reported that the technical error was the smallest for accelerometry when compared to the other two methods.

The mean average velocity for the video analysis (64.6 ± 16.5 cm $^{-1}$) was significantly greater ($p \leq 0.05$) than both the mean average velocity of the accelerometer and the photocell (60.8 ± 17.2 cm $^{-1}$, 61.7 ± 18.1 cm $^{-1}$ respectively). The Pearson's correlation coefficients among the three methods were all significant ($p \leq 0.05$). The photocell method had slightly higher amounts of variation (29.3%) when compared with film (25.5%) and accelerometry (28.3%).

When evaluating the entire lift only accelerometry and video motion could be compared. Thompson and Bembem found that the mean average power for the entire lift differed significantly ($p \leq 0.05$). There was a significant Pearson's correlation coefficient of $r = 0.95$ between full ROM methods. There was found to be less variation within the accelerometer (coefficient of variation (CV) 28.6%) than with the video analysis (CV = 29.2%). The technical error was also found to

be lower (58.5 W vs. 64.8 W). It was reported that the mean average velocity differed significantly ($p \leq 0.05$) and the variation within accelerometry was less than the variation within video motion analysis. There was a significant difference ($p \leq 0.05$) between the average total displacement of the accelerometer (43.2 ± 7.9 cm) and the video analysis method (47.4 ± 7.4 cm). The variation in the displacement measurement was greater for the accelerometer and technical error was the same. This difference was due to the over-simplified numerical method chosen to calculate displacement, rather than the sensor systems themselves.

Thompson and Bemben concluded that performance of all three methods was highly reliable in the computation of power. The researches reported an unexpected significant difference between the video motion analysis method and the other two methods. They ruled out mathematical integration error as they argued that the error of integration from velocity to displacement would have been larger. The percent differences between film and accelerometer did not increase from velocity to displacement measures (13.5% and 8.8% respectively). The possible equipment error suggested for the accelerometer included data acquisition error, inadequate filtering, calibration error, and or inadequate data acquisition software.

Possible equipment error for the photoelectric cell method was suggested as improper alignment of the photoelectric cells to the press bench. The possibilities of error suggested for the video motion analysis were errors in scaling or frame-to-frame displacement measurement. The scaling factor was determined by averaging 3 separate 10-second intervals on a meter stick used as a scaling rod. The researchers argued however that the Peak5 automatic digitizing minimizes displacement error by calculating the centroid of a reflective marker. Therefore they felt that the video motion method was the most accurate but were unable to substantiate this statement. The smoothing method used (if any) for video data was not indicated.

Even though there was a significant difference between accelerometry and video motion analysis they were highly correlated, with the accelerometer

slightly underestimating the video data. The authors maintained that this was to be expected given the precision of the accelerometer, but this is contrary to the conclusion that the video motion analysis was more accurate. The accelerometer senses instantaneous changes in acceleration live time throughout an event. Given adequate equipment and proper implementation its information is extremely accurate and precise. The technology of the accelerometer has been used, tested, and proven in many precision-based engineering areas such as the NASA space shuttle program. Thompson and Bemben use the accelerometer to collect acceleration data, and then **average** that instantaneous data to in their calculation for force. This averaging would result in a systematic under-estimation of the velocity as they report, but again this is a limitation of their methodology rather than of accelerometry. The final conclusion of the paper was that the accelerometer was a reliable and practically valid tool to evaluate muscular power when compared to video motion analysis and photoelectric cell methods. This study reveals one of the potential uses of the accelerometer for furthering our understanding of human movement.

One of the key components in the Thompson and Bemben study is that they are comparing average values of power. This brings up an interesting question. Are the average values of power, force, acceleration, or velocity adequate to explain the kinematics of load or the relationships between load and movement? We believe that these average values, do give valuable information in regards to the load, however, a continuous record of instantaneous values through the entire ROM may be more valuable. For example, two subjects may have the same average value but different peak values. The accelerometer to this point is the only technology that gives us the ability to measure instantaneous values throughout the ROM, which may be extremely valuable in the study of human movement. Unfortunately the purpose of the study by Thompson and Bemben did not consider inter-repetition, inter-set or other differences in acceleration related to load.

Acceleration and Exercise Dose/Response Studies

Since RJM is the critical element of load, the inability to accurately measure and control RJM may be the reason why previous exercise dose/response studies have shown relatively high degrees of variability (Fleck & Kraemer 1997). Acceleration dependent loading may be a plausible explanation, which accounts for why programs designed to develop NMS may have variable results. The extreme case being that an identical exercise program could substantially improve strength in one person, result in no change in another, and results in injury to another person undertaking the same program.

Investigating changes in acceleration is an important component required to understand changes in load when the orientation of segments are controlled. Knowledge regarding acceleration would provide insight into variation of load, which may occur during the performance of sets and repetitions due to changes in acceleration.

Most resistance training exercises that are performed are done so more than once (i.e. they are performed in a cyclical method of repeating repetitions and sets), (Fleck & Kraemer, 1997; Zatsiorsky, 1995; Baechle, 1994). Assessment of load using acceleration allows the researcher to ask the question "Is the loading different for each attempt? If so, when and possibly why?" To this end, continuously recorded accelerometry data was reported in a master's thesis on the bench press by Sylvain Lemelin in 1995, however no conclusions have been made using repetition-to-repetition acceleration data. The study by Lemelin examined the relationship between electromyography, activity of selected muscles, and the incline and supine bench presses. In this study accelerometry data was also collected and used to examine vertical accelerations of the bar during the exercise. The acceleration profile was shown to be an excellent method of detecting repetitions, as well as separating the ascent from descent phases of Bench Press.

Cadence/Velocity

Controlling cadence is one of the methods in which practitioners attempt to control the loading during exercise. This is commonly done by verbal prompting, using the *comfort zone* (pace at which the individual feels most comfortable) and occasionally by using a metronome. As defined previously the cadence is the rate at which the repetitions are completed, that is the number of repetitions per second or the average duration of each repetition. In free weight training, phases of the movement are set, or timed by this cadence. Therefore the movement of the exercise is prescribed to go through a given range of motion or a certain number of repetitions in a constant interval of time. Where the ranges of motion are exact, and the timing intervals exact, the average movement velocity can be computed. Although the average velocity can be roughly controlled with an established cadence, the within repetition velocity can vary dramatically between repetitions even at the same average value. This clearly would arise from differences in acceleration during the repetition. In regards to the actual RJM involved in the motion, acceleration is the key component related to the magnitude of force, velocity is not explicitly involved. Even two people performing an exercise at the same cadence (same average velocity) can theoretically have dramatically different acceleration profiles.

Physiological Components

Human movement requires a complex combination of physiological factors including neural and mechanical components. To apply its forces upon the external world the body uses its muscles to create a moment about joints. The neuromuscular system includes all the components of the human body that are required to achieve motion of all or part of the body. It consists of the central nervous system, the skeletal system (bones and joints) and the muscular system (McArdle, Katch, & Katch, 1991). Traditionally the study of strength development has been broken into two primary areas of scientific study, the study of neurophysiology and that of muscle physiology. In recent years scientists have begun to bridge the gap between the neurological system and the muscular

system, through interdisciplinary studies aimed at both the muscular and neural systems. The ability of the nervous system to appropriately activate the muscles is an integral component of strength development (Enoka, 1994; Sale et al., 1981). It is important to consider that both the neural and muscular systems adapt during resistance training programs.

Summary

Acceleration is clearly identified as a component of load based upon the Newtonian equations of motion, which are used to derive moments necessary to produce an observed motion. Acceleration of body segments and free weights have not yet been systematically evaluated in resistance training. The first step in understanding the kinetics of free weight exercise is the examination of the variation in acceleration during free weight exercise. The purpose of our study is to examine acceleration both within and between repetitions and sets, as well as to contrast acceleration differences between trained and untrained female subjects.

STUDY RELEVANCE

The development of the NMS is far reaching to the general population in all aspects of life from health to high performance athletics, and labor. Our ability to move is based upon the ability to generate external force using muscles and the skeletal structure. Strength, endurance, and flexibility must then be examined relative to the individual and task in question. For example, the absolute requirement of the NMS for squatting weights of over 800 pounds by an elite power lifter is different than that required by an elderly person to stand from a chair. However, depending upon the population, both tasks may represent a maximum effort. It is therefore important to be able to assess NMS requirements and levels so that appropriate exercise prescriptions may be made, not only from task to task but also from population to population.

The generation, development and understanding of the NMS are important in the areas of health, athletic performance, and rehabilitation. The accurate assessment of moment generating requirements placed upon the body would allow the rehabilitative, fitness, or coaching practitioner, as well as the researcher to better understand the generation and control of motion and force. This would make it possible to create NMS development programs that are more efficient and specific.

The ability to live a healthy independent and productive life is partially dependent upon our body's capacity to perform various physical tasks, which involve the movement of the human body. The U.S. Surgeon General's Report on physical activity and health concluded that there are increased health risks associated with an inactive lifestyle (U.S. Department of Health and Human Services, 1996). The American College of Sports Medicine goes on to add in their position paper, that a healthy lifestyle should include resistance exercise (ACSM, 1999).

The activities of daily living scales (ADL) were developed to measure functional capacity for every day activities (Myers, 1992). These activities or tasks usually require some level of strength about various joints, as would be

required for standing from a chair. These scales are used to assess independence as well as other factors that may change with injury, pathology, or aging. It has been documented that neuromuscular strength is an important factor in aging (Narici, Bordini, & Cerretelli, 1991; Vandervoort & McComas, 1986). Recreation is often considered an important part of a healthy lifestyle. The ability to participate in many recreational activities also depends on some level of NMS.

The next area that one may consider is that of physical injury. There are two main issues when discussing injury and NMS, injury prevention and injury rehabilitation. Injury prevention is related to the ability of the neuromuscular system to handle the physical stresses required to perform a task and or activity. If the level of neuromuscular strength to successfully complete a task or activity is not present, then injury may result. The development of sufficient strength and endurance of the neuromuscular system is critical to the prevention of these injuries. The overall purpose of resistance exercise is to improve function (Kisner & Colby, 1996). Understanding loads and load variation during movement (loading profile) is important for further understanding of the benefits of NMS training on injury prevention. Secondly, injury rehabilitation plays an important role in one's standard of life, the economy (due to health care and production), and athletic performance. In today's society there is a high value placed on athletics. This may be a dollar value, or a value of social pride, acceptance or stature.

As mentioned above, a clear understanding of load is critical to the development of the effective rehabilitation exercise programs. Issues such as the speed of NMS development, injury potential and over-training are crucial not only to the high performance athlete but also to the recreational athlete who must attend work on Monday. Injury to either of these athletes may be financially devastating. Little is known regarding acceleration differences during exercise, and it is critical for research to be undertaken to begin to discover the relationship between acceleration and exercise.

This study will attempt to examine the acceleration profiles or patterns observed during free weight exercises. This knowledge will aid researchers, therapists and coaches to better understand load and how its manipulation affects the development of NMS. In this experiment we chose the use of the prone dumbbell row because it closely mimics the bent over dumbbell row (a common exercise used in resistance training, and can be observed both in clinical settings as well as athletic settings).

One objective of this study is to identify the acceleration profiles for free weight exercise movements. Repetitive movements like those in free weight resistance exercises have repeatable and predictable acceleration patterns, which may be different for people with different levels of training. A comprehensive understanding of load is essential for research that examines the dose/response relationship of exercise. A clear understanding of the “dosage” is mandatory in order to characterize the response and attribute the response to a certain aspect of the “dosage” or load. By combining a biomechanical perspectives with exercise physiology, this work will attempt to improve our understanding of load in exercise – a topic which is not well elucidated in research journals, books, or coaching technical manuals.

OBJECTIVES

The primary objective of this study is to examine the inter-repetition and inter-set variation of the acceleration profiles during a standardized free weight exercise. The secondary objective of the study is to perform a preliminary comparison of accelerations between trained and untrained subjects in the execution of a standardized free weight exercise.

HYPOTHESES

1. There would be a decrease in peak accelerations with repetitions within sets of the standardized exercise, the prone dumbbell row. Accordingly, we hypothesized that there will be a decrease peak-to-peak acceleration over successive sets of the standardized exercise.
2. Trained people will exhibit less variability in acceleration than untrained individuals.

LIMITATIONS

The first limitation is that the exercise used in this study has been modified from that normally observed in the weight room in order to permit control of potentially confounding factors such as accessory or compensatory body motion. The ability to generalize the results may be limited by this modification. The bent over dumbbell row was selected as the base exercise and it was modified to be the prone dumbbell row. We believe this exercise is important as it is commonly observed in most weight rooms, and general exercise literature (Baechle, 1994; Fleck & Kraemer, 1997). It is also similar to many common actions seen in everyday life such as reaching down and picking up an object with one hand. In our study we have asked the subjects to lay down in a prone position with their dominant shoulder supported on the bench and their dominant arm hanging off of the side of the bench. This allows us to reduce or eliminate any compensatory action and acceleration of the torso during the test. As this is the first study to begin to understand acceleration, it is important to control as many confounding factors as possible.

Another limitation is that we did not measure the instantaneous acceleration of each of the body segments involved in the motion, only the dumbbell. Although dumbbell acceleration is a primary parameter in derivation of instantaneous resultant joint moments, the accelerations of the upper arm and forearm also have important influence on the instantaneous RJM about each of

the joints (shoulder and elbow) involved in the motion. As such, the results of this study are limited since segmental acceleration was not measured with multiple accelerometers.

Further, this study is limited by the fact that we did not compute the instantaneous resultant joint moments about the primary joints (the shoulder and elbow). However, since the range of motion and the segmental orientations were controlled, which influence the magnitude of the moment of weight, the only remaining variable in the computation of RJM is acceleration.

ASSUMPTIONS

The primary assumption in the study is the consistency of the pattern of movement. If the subject changes the relative orientation of their joints throughout the ROM (in essence changing the exercise), then our ability to examine inter-repetition and inter-set differences in loading is compromised using acceleration alone. The experimental set-up and the exercises used, limits this possibility, however without a direct measure of this potential variable we are left to assume that the subject is repeating the same motion for each repetition. In an effort to account for this we are using a flexible stick as a marker at the top of the ROM. As it is a point in space to which they must raise their elbow we can assume a very similar ROM as the point must be touched each repetition.

A second assumption is that the subject does not perform any compensatory movements. We attempt to control for this motion by blocking the shoulder with the bench upon which they are lying. We also terminated the experimental exercise at the first sign of compensatory body movements.

Our last assumption is that our evaluation of a self reported weight-training history is valid in reflecting a difference between our two groups – trained and untrained. We also assume that the people with weight training experience are homogeneous.

METHODOLOGY

Experimental design

This is a cross-sectional study of two groups (trained and untrained) performing a standardized free weight exercise- a prone dumbbell row.

Subjects

There were 26 female subjects recruited for this study with 18 being classified as trained and 8 untrained.

Inclusion Criteria

The inclusion criteria for our study included an age range of 18 to 35 years of age. Subjects had to be healthy defined as not having any type of medical problems within the last 12-month period. The final criterion was that all subjects had to be right hand dominant, as defined by the hand they would use to throw a ball.

The trained and untrained groupings for this study were determined based upon they're previous and current experience with resistance training as assessed by a screening questionnaire. The trained group included subjects who had participated in some form of upper-body resistance exercise at least 2 times per week, for minimum of 30 minutes per session, for the past 6 months. These subjects were familiar with the Bent Over Dumbbell Row exercise or similar exercise.

The untrained classification was based on subjects with no prior consistent (> 2 time per week) weight lifting experience and subjects with no prior elite competitive (provincial, national, university or professional) experience.

Exclusion Criteria

There were several exclusionary parameters set for this study. Subjects outside the above specified inclusion criteria were excluded. Subjects that reported any of the following characteristics were also excluded based upon a questionnaire (Appendix A), restriction in range of motion of the right upper extremity or any significant history of injury to right upper extremity, known cardiovascular disease or any other medical conditions which preclude involvement (i.e. history of arthritis, other inflammatory conditions affecting the back, shoulder, arm or hand), and pregnant or breast-feeding females (Appendix A).

Recruitment

A sample of convenience was recruited by word of mouth from the Bannatyne Campus and Fort Garry Campus of the University of Manitoba. Subjects were required to read the study paraphrase (see Appendix B), and upon completion were given an informed consent form (see Appendix C) to sign prior to participation in the study. Subjects were not provided any reimbursement for their participation in this study, nor were they responsible for any costs directly related to the study.

Ethical approval

The Faculty of Medicine, Human Ethics Committee, has granted ethical approval for this protocol.

PROCEDURE

The experimental procedure was performed in the following order with minimal rest between components other than where specified. Each of the components of the experimental procedure is described later in the Methodology.

1. Familiarization with prone dumbbell row and warm-up (stretches)
2. 12 repetition maximum test of prone dumbbell row.
3. 10 minutes rest
4. 3 sets of 10 repetitions at 12 repetition maximum weight with 120 second rest between sets (that is, 3 x 10 @ 12 RM).
5. 120 second rest
6. 1 set of 10 repetitions with a pause introduced at the midway point of the repetition. This final set was also performed with the 12 repetition maximum weight.



Figure 2. Sequential photographs of the movement sequence for the prone dumbbell row.

Prone Dumbbell Row

Subjects were instructed to lie face down (prone) on an exercise-testing bench (Figure 2). The bench was high enough that the upper limb could hang off the side of the bench keeping the hand a minimum of 20 cm from the ground. This allowed the subject to use their dominant arm to hold the dumbbell without the dumbbell contacting the floor. The whole of the body was supported by the bench surface. The subjects were instructed to keep the chest and shoulders on the surface of the dynamometer bench. The subject was allowed to use the non-dominant arm to hold on to the bench. From a fully extended and vertically downward arm position, the dumbbell was raised vertically until the elbow contacted the flexible marker stick located at a specific height. This height

corresponded to a specific segmental position where the upper arm was parallel to the floor. The dumbbell was then lowered vertically back to the start position without contacting the ground. The fact that the elbow was raised to a marker point insured that the range of motion and movement pattern was similar for each repetition. The speed of movement was not controlled as subjects were permitted to choose their own cadence. However, a limit of a 5 second repetition duration was used.

Familiarization + Warm up

All subjects were asked to complete a warm up, which included two stretches while sitting in a chair (Figure 3). The subjects were instructed to maintain a “tight midsection” during all stretches.

Behind the neck stretch (Baechle p. 301)

- Sitting in a chair
- Flex the right arm and raise the elbow above the head
- Reach the right hand of the down towards the left scapula
- Grasp the right elbow with the left hand – pulling the right elbow towards or behind the head depending on flexibility
- Hold for two sets of 10 seconds
- See figure 3 – right hand panel

Cross the arm horizontally in front of the chest (Baechle p. 301)

- Sitting in a chair
- Slightly flex (15-30 degrees) the right arm and adduct it horizontally across the chest.
- Grasp the upper arm just above the elbow, placing the left hand on the posterior side of the upper arm
- Pull the right arm across the chest (towards the left) with the left hand.
- Hold for two sets of 10 seconds

- See figure 3 – left hand panel



Figure 3. Warm up stretches. Right hand panel one is a behind the neck stretch. Left hand panel is the in front of neck stretch.

Exercise Protocol

All subjects were given uniform instruction on executing a prone dumbbell row in the following sequence:

Instruction for the prone dumbbell row exercise:

1. verbal information
2. demonstration of prone dumbbell row
3. familiarization with a lightweight dumbbell (5 lb)
4. correction of the skill by investigator

Description of prone dumbbell row provided to the subjects:

1. The subjects were instructed to lie on the exercise bench in the position described above.
2. The right arm was to hang off the side of the bench.
3. While holding the weight at full extension, neither the weight nor the hand was allowed to touch the ground.
4. The subject was instructed to keep the chest on the bench at all times.
5. The subject was instructed not to rotate the dumbbell in their hand.
6. The dumbbell was pulled upward in a vertical direction until their upper arm was parallel to the floor.
7. The subject then lowered the dumbbell back to the extended position.
8. The inter repetition time was not permitted to exceed 5 seconds. With the exception of set number 4 in which pauses were imposed where no time limit was imposed.
9. This sequence was repeated until the subject was comfortable and capable of performing the exercise.
10. Reasons for cessation of exercise and or experiment
 - if at any time the subject wishes to stop
 - if the subject shows or expresses pain
 - if accessory or compensatory movements are identified

Determination of weight for the prone dumbbell row exercise

The 12-repetition maximum (12 RM) weight used for the experimental exercise was determined using the following procedure. A 12 RM is the maximum amount of weight that a subject can lift in good form for no more than 12 repetitions. A rest period of 120 seconds was provided between attempts. All attempts were recorded and a maximum of 5 attempts were permitted.

Table 4. Protocol outline for sets and repetitions for 12 RM Testing.

Set	Repetitions	Weight	Rest/Recovery
1	12	?	120 seconds
2	12	?	120 seconds
3	12	?	120 seconds
4	12	?	120 seconds
5	12	?	120 seconds

The initial selection of weight was determined by verbal interaction with the subjects and visual assessment during familiarization. The weight for the following set was determined by the assessment of the last set as well as verbal interaction with the subject. If in the last set the repetitions were completed without any difficulty, then a higher weight was attempted. If accessory or compensatory movement were identified, then the weight from the previous set was used. A rest interval was imposed of 10 minutes before the experimental exercise was commenced.

Acceleration Measurement Protocol

The experimental protocol for recording acceleration during the prone dumbbell row involved measurement of acceleration during four sets of ten repetitions at a 12 RM weight (Table 5). The rest breaks between sets were set at 120 seconds. The first three sets were completed in a continuous fashion, i.e. no pause was allowed either between each repetition or at the mid-repetition point. For the final set, a pause was introduced both between repetitions and at the midpoint of each repetition (the end of the ascent of each repetition).

Table 5. Protocol outline for sets and repetitions for Experiment.

Set	Repetitions	Weight	Rest/Recovery
1	10	12RM	120 seconds
2	10	12RM	120 seconds
3	10	12RM	120 seconds
4	10	12RM	

Instrumentation

Figure 4 illustrates the basic set up for recording acceleration during the prone dumbbell row including the equipment, instruments, and subject positioning and exercise orientation. The equipment and instruments used in this study included (See Figure 4);

1. a uniaxial accelerometer
2. an operational amplifier with adjustable gain and offset control
3. a digital oscilloscope
4. a computer based data acquisition system
5. a specially modified dumbbell

The accelerometer was attached to the dumbbell on a specifically modified collar (B in Figure 4). The accelerometer is connected to the operational amplifier (E in Figure 4) through a cable. The amplified accelerometer waveform is connected to an oscilloscope (C in Figure 4) for visual feedback and a computer based data acquisition system (D in Figure 4). A flexible stick was used as a physical cue (A in Figure 4) to insure that the subject performed the task through the specified range of motion and in a similar plane of motion.

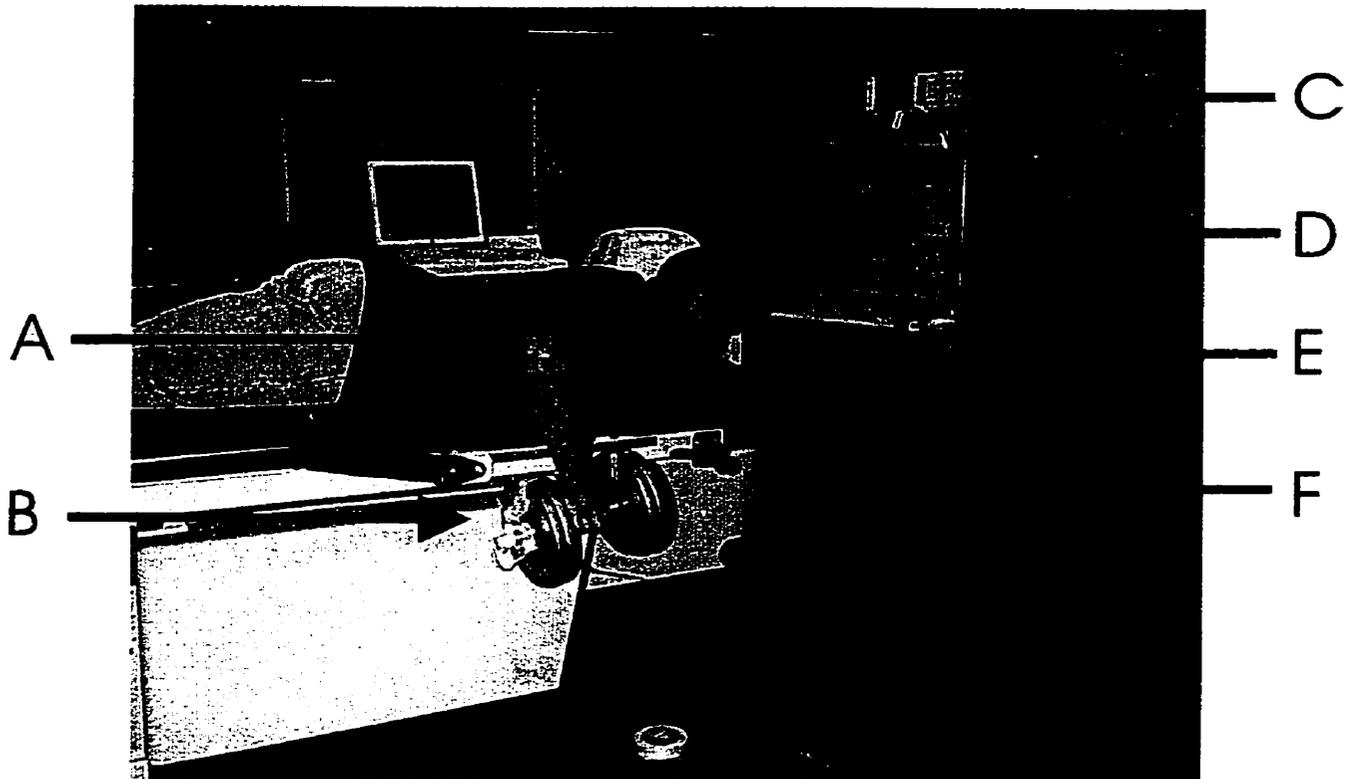


Figure 4. Experimental setup. A- Range of motion marker. B-Dumbbell, C-Oscilloscope D- Data acquisition system, E – accelerometer amplifier, F- EMG system.

Dumbbell

A solid steel, chromed dumbbell (Starlock 2) with locking, spin collars was used. One of the star locking collars was modified to provide a flat surface for mounting the accelerometer on a flush surface that could be easily oriented vertically. Iron plates of various weight increments were available for varying the overall dumbbell weight. The weights of all dumbbell components were measured using a calibrated weigh scale and labeled.

Accelerometer

Acceleration was measured with an IC Sensors 3022 piezoelectric linear (uniaxial) accelerometer (Figure 5).

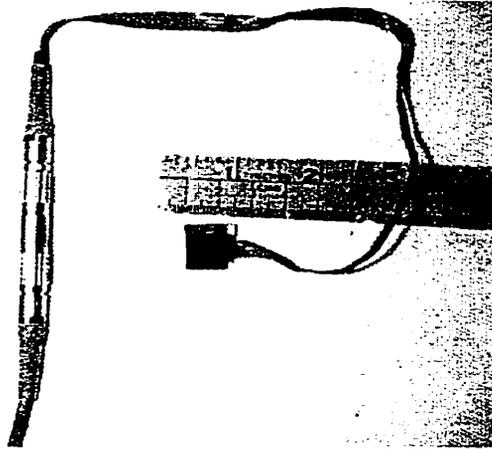


Figure 5. A linear, uniaxial accelerometer and connector system.

The accelerometer was placed on the flat surface of the modified spin lock collar of the dumbbell with two-sided adhesive tape (see B Figure 4). The dumbbell was rotated to orient the accelerometer with the line of action of gravity (vertical) prior to each test. This orientation was verified by oscilloscope since the voltage output of the accelerometer is indicative of the orientation of the accelerometer. A tension relief loop was made in the cable to minimize cable artifact picked up by the accelerometer.

Accelerometer Calibration

The accelerometer signal was calibrated using the gravitational acceleration method (Figure 6). In this method, the uniaxial accelerometer is oriented in three controlled positions. Vertical corresponding to the known gravitational acceleration of $-1.0g$ (-9.8m/s^2), inverted corresponding to $+1.0g$ (9.8m/s^2), and on its side ($0.0g$). The voltages corresponding to each of the three known or reference accelerations positions are recorded using the data

acquisition system. This calibration file is stored for analysis. The scale factor (multiplier) and zero 'g' offset value were derived from the file and used for calibrating the accelerometer voltage waveform. Linear regression between the voltage values and the actual calibration values revealed a strong linear relationship ($r=0.999$, $p < 0.05$).

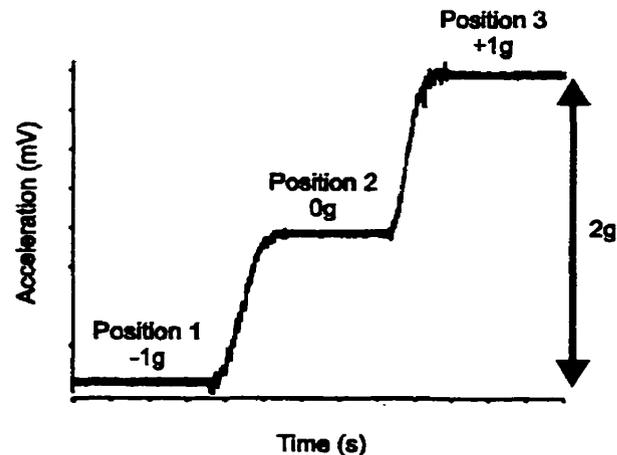


Figure 6. A representative accelerometer waveform for a calibration trial.

For all the trials, the 1 g accelerometer voltage was set to zero acceleration relative gravity. In other words, the acceleration response of the accelerometer due to gravity was 'nulled out'. In this way, the acceleration magnitude reflected the acceleration arising from the control of the dumbbell by the subject. Also, similar to the method of Thompson and Bemben (1998), the acceleration data could be used to directly compute the "effective weight" of the dumbbell during various phases of the motion based upon Newton's second law, $F=ma$. For example, a value of 0.5 g would reflect that an additional $\frac{1}{2}$ g of acceleration was applied to the weight by the subject resulting in the weight being 1.5X that of normal for that instant in time. All acceleration data reported in this thesis have been adjusted in this manner.

Acceleration Profiles

Phases of Acceleration

An acceleration profile is a graphical representation of the relationship between acceleration with respect to time during movements including cyclical ones like free weight exercises. A typical acceleration profile for the four sets of prone dumbbell row is shown in Figure 7. The peak-to-peak acceleration differences can be readily observed in the acceleration profile, as well as the inter-set rest interval (periods of zero acceleration).

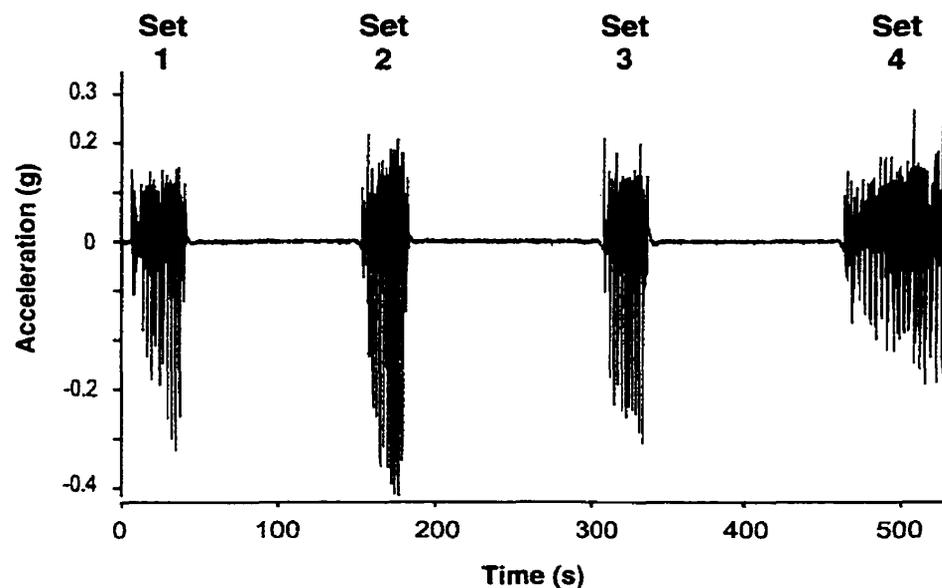


Figure 7. A representative trial for a trained subject showing the band-passed filtered acceleration profile for four sets. The inter-set rest interval is evident between each set.

Standardized Nomenclature for Phases of Motion

An important development in understanding the influence of acceleration on loading during free weight exercise was the development of nomenclature suitable for analysis of the accelerometer signals of cyclical activity. We have developed a new nomenclature, which creates terminology that can be used in research and practice for evaluation of sub-components of a single repetition for repetitive motions. This nomenclature can be applied to motions in the

gravitational plane (primary motion in the vertical plane) or motions that are normal to the plane of gravity (e.g. a motion in the horizontal plane). The acceleration profile of one repetition of the prone dumbbell row (and any repetitive or cyclical motion) can be broken down into four major phases independent of gravitational acceleration; Phase 1 (P1), Phase 2 (P2), Phase 3 (P3), and Phase 4 (P4). These phases can be seen in Figure 8. Phase 1 starts from the initial extended arm position at A (zero velocity and zero acceleration). P1 is a positive acceleration phase that peaks at point B and terminates at point C corresponding to the zero crossing point. P2 commences with the zero crossing of acceleration consisting of a negative acceleration phase. During the P2 phase, the dumbbell begins its upward “deceleration”. The ascent phase (raise) corresponds to combination of P1 and P2. A zero acceleration period occurs when the person holds at stationary position (E). During the ‘hold’ position, the velocity and acceleration are very close to zero.

Phase P1 and P2 are concentric muscle actions, while P3 and P4 are eccentric actions. The hold phase from E to F in figure 8 is an isometric contraction.

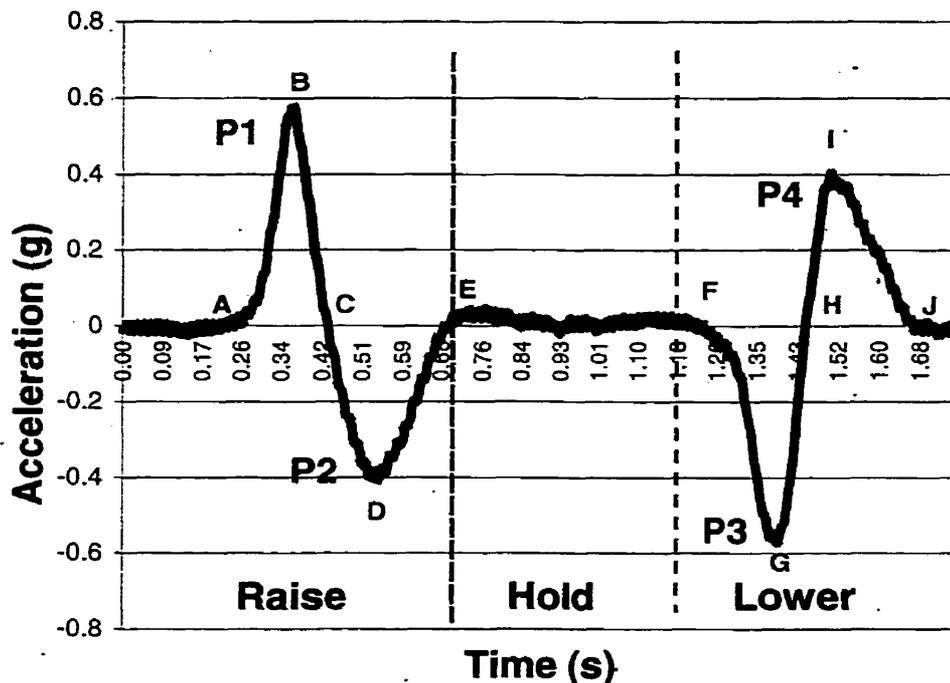


Figure 8. Nomenclature used to define the phases of acceleration for a single repetition with a pause at the mid repetition point using illustrative data set.

The second half of the repetition (lowering or descent phase) begins at F. at the end of the pause. As the descending motion begins, the acceleration increases in the downward direction (negative). It is important to remember that an object or body segment may be moving in one direction (positive or negative velocity) yet experience acceleration in the opposite direction (Enoka, 1994). The dumbbell then peaks (G) before its acceleration decreases again to zero (H) signaling the completion of P3. The sign of acceleration changes to positive as the dumbbell begins to “decelerate” or slow to a stop near the start of the ROM. This corresponds to P4. This deceleration peaks (I) and then decreases until the dumbbell comes to a stop (J). Note that P1 and P4 have the same sign; the acceleration to start the dumbbell upward is directed in the same manner as that which is needed to stop the dumbbell during the descent (positive or upward acceleration needs to be applied).

Acceleration Profiles of Continuous Cyclical Movements

It is not common to advocate a pause at mid-repetition, so most free weight resistance exercises exhibit a blend or combination of phases (Figure 9). The lack of a pause between repetitions, or continuous motion, results in the P4 from the previous repetition blending with the initial phase (P1) of the next repetition. Similarly, the lack of an enforced pause at the midway point (between the ascending and descending of the dumbbell) causes the end of the ascending motion (P2) to blend with the beginning of the descending action (P3). It is also important to remember that it is not possible to tell the direction of acceleration from the direction of movement (Enoka, 1994). Figure 9 shows blended phases during continuous repetitions of the prone dumbbell row.

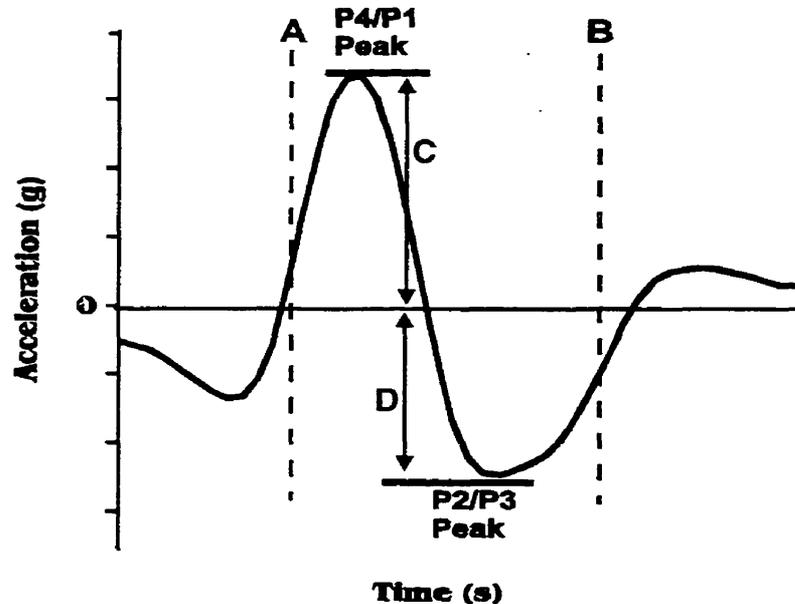


Figure 9. An illustration of a acceleration profile of a continuous prone dumbbell row exercise repetition. P4 of the previous repetition combines with P1 of the current repetition. P2 and P3 blend without a pause at mid-repetition.

Figure 7 is an example of an acceleration profile for all four sets of the prone dumbbell row for a trained subject. At this time scale, the individual repetitions cannot be distinguished. The positive or upward deviations in acceleration correspond to the P4/P1 phases of the acceleration data, while the negative deflections of acceleration correspond to the blended P2/P3 phases of

jerk plot (derivative of the acceleration data) to identify the inflection point between the P2 and P3 phases (not shown). In the fourth set, a pause was enforced both between repetitions and at the mid-point of each repetition resulting in an acceleration profile in which each of the four phases was entirely separate.

Data Acquisition

Labview (National Instruments, Version 5.0) software was used to acquire the accelerometer signal. An analog to digital converter (AT-MIO-16E-2, 16 analog inputs; 12-bit resolution; 500 kS/s sampling rate max, National Instruments) was used to sample the accelerometer signal at 250 Hz. The digitized accelerometer data was stored to disk for each trial. The gain of the accelerometer amplifier was adjusted to provide maximum input to the data acquisition system.

Low and High Pass Filter Selection

Each of the accelerometer trials was filtered using a combination of a low pass filter (removing high frequencies) and a high pass filter (removing low frequencies) to preserve an intermediary band of frequencies related to the motion and reject signals which were unrelated to the motion. A second order Butterworth digital filter was used for this purpose. The accelerometer data was sent through the filter twice (a recursive filter), in the first pass the data is sent through in normal order and during the second pass the data is sent through backwards. This two pass method has two effects; 1) sharpening of the cutoff characteristics of the filter resulting in a forth order filter (double filtering), and 2) zero-phase lag in the signal arising from passing the signal backwards to restore any phase lag that was created.

Some of the acceleration profiles contained unwanted high frequency vibration or 60 Hz Line noise, which may have arisen from muscle contraction or

from amplifier noise. Also the accelerometer signal may have also contained very low frequency signals due to rotational offsets created by orientation changes of the accelerometer. In order to preserve the movement related acceleration information, a band-pass filter was employed. A band-pass filter is achieved by combining both a low pass and high pass filter.

An objective method for establishing the cutoff frequency for each of the filters was established as follows. In order to determine the cutoff frequencies we used a process whereby the acceleration waveforms were consecutively filtered with a systematic variation of filter frequency for each of the filter types (low and high). We used a representative acceleration profile, as well as an “extreme” acceleration profile for cutoff selection.

The peak acceleration of the P4/P1 phase was measured using a cursoring system in our analysis software. The magnitude of this peak acceleration was plotted with respect to the cutoff frequencies used (Figure 11 and 12). The attenuation of the peak P4/P1 acceleration was plotted with respect to cutoff setting for high pass filter frequencies (Figure 11) and the low pass filter frequencies (Figure 12). Using these graphs, we can observe the “breaking point” where the change in cutoff frequency starts to attenuate the magnitude of the peak acceleration. The cut-off frequencies were selected in a conservative manner so that the movement related acceleration magnitudes were preserved. The derived band-pass filter settings used for all the acceleration trials (Figure 13) was specified with a low pass cutoff of 10 Hz and a high pass cutoff of 0.1 Hz. Thus a band of accelerometer signal frequencies were preserved between 0.1 Hz and 10 Hz corresponding to the movement related acceleration.

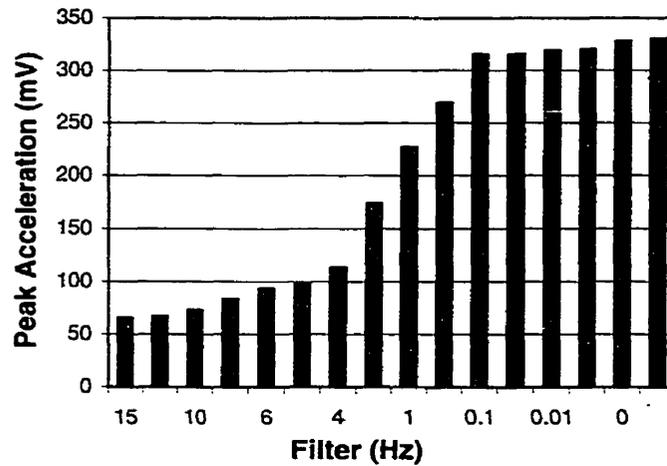


Figure 11. Attenuation of the peak P4/P1 acceleration with different high-pass filter cutoffs.

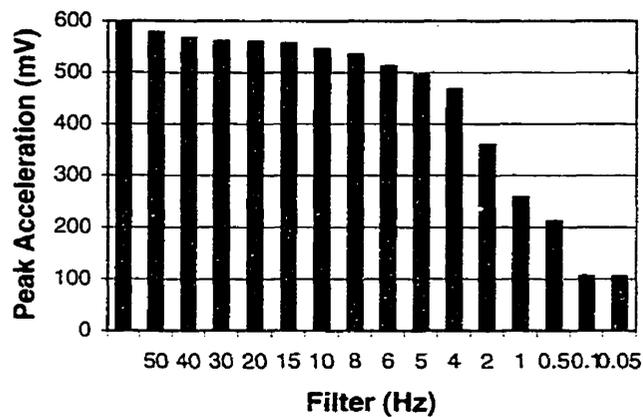


Figure 12. Attenuation of the peak P4/P1 acceleration with different low pass filter cutoff frequencies.

Orientation of Accelerometer

A uniaxial accelerometer was employed in this study, which is sensitive to orientation changes during the motion. Even though we used a high pass filter to remove unwanted offsets arising from orientation changes in the accelerometer (rolling the dumbbell), we were able to confirm that rotation-induced changes in

acceleration were minimal by visual inspection using the oscilloscope in real-time and by examination of the raw or unfiltered acceleration profiles on a trial by trials basis for signal offsets. There were three trials that revealed systematic offset due to orientation changes of the accelerometer and in all of these cases the offset was very small. These data were retained for further analysis due to the negligible impact of rotation. Further, between each set the dumbbell was rotated to a vertical orientation.

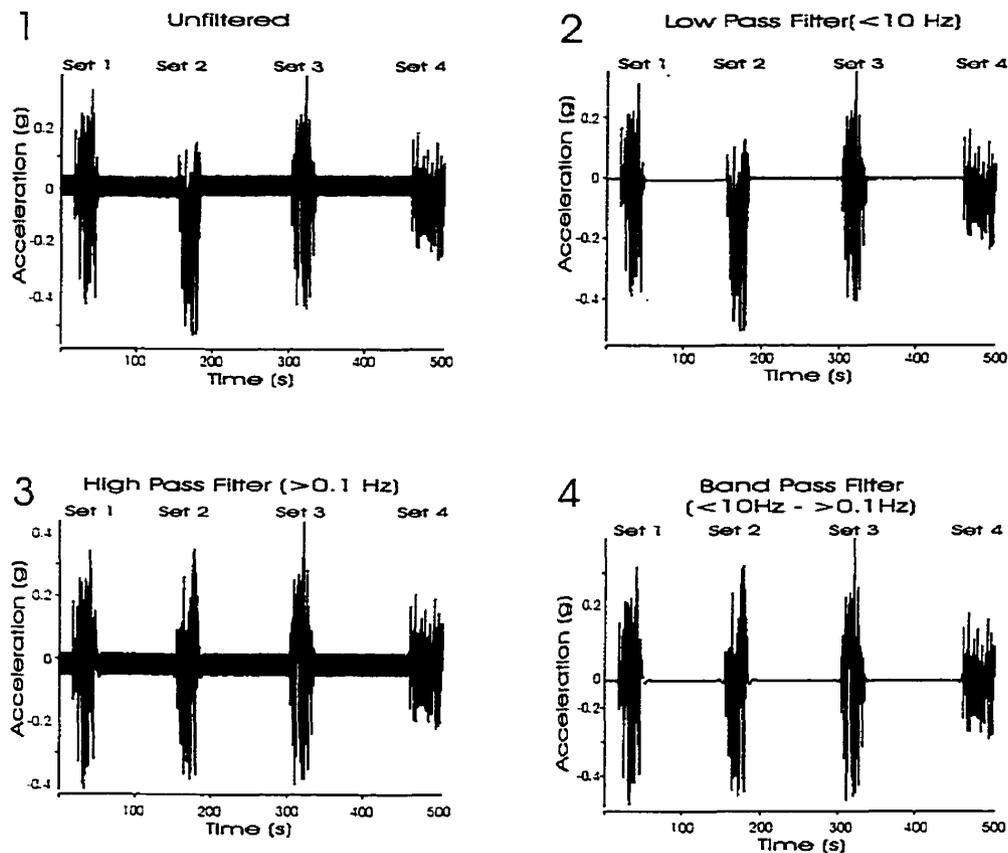


Figure 13. Representative data showing the effect of high, low and band-pass filtering of acceleration data.

Analysis

The data was analyzed using custom software (Analysis, University of Manitoba <http://www.ssrc.umanitoba.ca/doc/>). It was used to delineate each repetition using an automated repetition (cycle) detection method. Each repetition

was detected by software by setting a threshold acceleration value, which had to be exceeded for a repetition to be detected. This threshold was set visually for each trial but not for each repetition. In addition, minimal repetition duration was automatically determined to avoid false positive triggers.

The software automatically detected and recorded the peak or maximum acceleration during the blended (P4/P1) and the peak minimum acceleration (P2/P3) values within each cycle of movement. In addition, the software detected and recorded the absolute peak-to-peak (PP) acceleration difference within each repetition. For continuous repetitions, the distinction between P4 and P1 becomes blurred, and as such the start of each repetition becomes difficult to precisely determine. This did result in some P4 measurements being categorized as P1. This would result in slightly different peak-to-peak magnitudes depending upon the method used for computation. In order to account for this, the peak-to-peak magnitudes were also derived by differencing the maximum and minimum acceleration values for each repetition (MM). The peak-to-peak acceleration data was represented by MM and PP in the results. There were no significant differences in peak-to-peak acceleration magnitudes between PP and MM methods.

Statistical Analysis

The peak P4/P1 and P2/P3 and PP accelerations were the dependent measures used for statistical analysis. Repeated measures ANOVA were employed to examine differences in peak-to-peak accelerations with repetitions and sets. Post-hoc comparisons were performed using Tukey's HSD test. Independent t-tests were used to compare between groups for single parameter measures. In some cases, pair t-tests were used for within group comparisons of peak acceleration between specified repetitions. Pearson-product moment correlation was performed between P4/P1 and P2/P3 peak acceleration values. An alpha level of 0.05 was used for inferential statistics. All plots were represented with error bars corresponding to the standard error of the mean.

RESULTS

Subject characteristics

Table 6 shows the characteristics of the trained and untrained groups. Independent t-tests were performed to identify significant differences between the two groups for the indicated parameters. The RM value for the trained group was significantly greater than the untrained group by 3.29-kg (32.2 N or 7.2 lbs.).

Table 6. Subject characteristics. The standard deviation is shown in parentheses.

	N	Age (yrs)	Body Mass (kg)	Height (cm)	BMI	12 RM Dumbbell Mass (kg)
Trained	18	31 (4)	64.9 (9.58)	165.58 (6.59)	23.6 (2.5)	12.87 (2.72)
Untrained	9	28 (6)	60.82 (9.06)	163.22 (5.39)	22.8 (2.6)	9.58 (2.34)
		NS	NS	NS	NS	p < 0.01

12 RM testing

The protocol for the 12 RM testing was the same for both groups. The resulting average number of sets used for determining the 12 RM value for the trained group was 2.1 sets. In addition, one set was performed with a low weight (5 lb or 2.2 kg) for familiarization. This was not significantly different from the untrained group where an average of 2 sets was needed for the determination of the 12 RM weight.

Continuous Sets

Repetition Duration

All subjects were able to complete all 30 repetitions (at their individual 12 RM load) during the first 3 sets of the experiment. The computer software was used to determine the repetition duration for each repetition automatically. Figure 14 shows the trained group and Figure 15 shows the untrained group. Repeated

measures analysis of variance revealed a significant set effect ($p < 0.01$) but not group or interaction effect. Post-hoc analysis revealed that repetition duration for set 4 was significantly longer than sets 1, 2 or 3 ($p < 0.05$) for both groups and that sets 1, 2 and 3 were not significantly different.

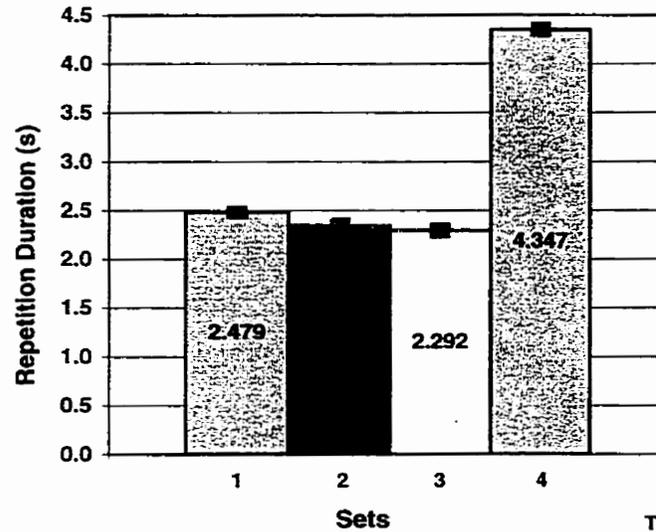


Figure 14. Average repetition duration (\pm SE) for each set for trained subjects.

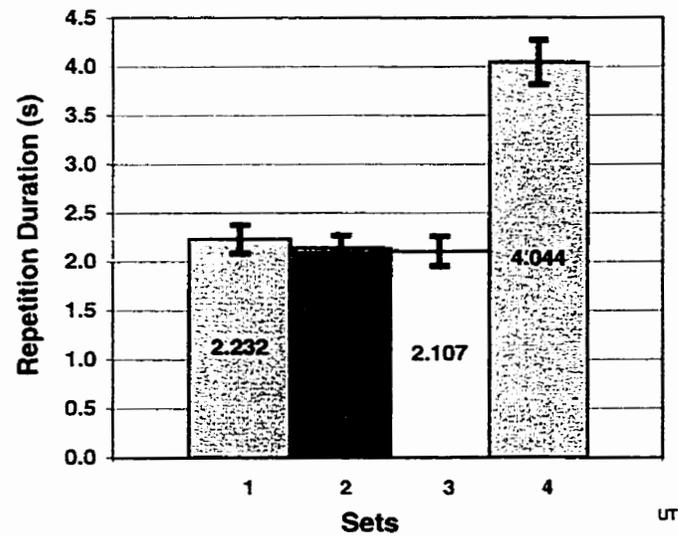


Figure 15. Average repetition duration (\pm SE) for each set for untrained subjects.

Within Set, Inter- Repetition Acceleration Magnitude

Repeated measures ANOVA was used to examine the within subject differences in acceleration between sets and the differences between groups. A significant set effect ($p < 0.001$) was revealed but there was no group or interaction effect.

Post-hoc analysis was performed to reveal that the significant differences between sets existed between set 4 and all other sets, between set 1 and set 3, and between set 2 and set 3.

Repeated measures ANOVA was performed on PP acceleration values for all 30 repetitions of the first three sets to reveal effects of repetitions and differences between groups. A significant repetition effect ($p < 0.0001$) was observed without a group or interaction effect.

Based upon the repetition effect revealed by the ANOVA, further analysis of differences between repetitions was explored using specific t-tests. Table 7 illustrates the relationships between the repetition 1 and repetition 2 acceleration magnitudes for each set and each phase. The peak acceleration for P1 for the first repetition was significantly lower ($p < 0.05$) than repetition 2 for all continuous sets of the trained group. Remember that the first repetition of each set only contains P1 (not contaminated with a P4 of the previous repetition). Similarly, the first repetition peak P2/P3 value and the PP acceleration values were significantly ($p < 0.05$) lower than repetition 2 for all sets for the trained group.

Table 8 shows the relationships between repetition 1 and repetition 10 of each set in each of the phases. The peak P1 acceleration for the trained group was similarly significantly lower ($p < 0.05$) in all sets. This was not true for the peak P2/P2 and PP magnitudes. Repetition 1 was significantly lower ($p < 0.05$) than repetition ten in only set 1.

For the untrained group, the peak P4/P1, P2/P3 and PP accelerations for repetition 1 were significantly lower ($p < 0.05$) than that of the second repetition in set 3 for P4/P1 and set 1 for PP. The untrained group also showed a significantly lower ($p < 0.05$) repetition 1 than repetition 10 for sets 1 and 3 of the peak P4/P1 values and set 2 for peak P2/P3 values.

Table 7. Paired t-tests of peak accelerations for P4/P1, P2/P3 and PP between repetition 1 and repetition 2 for each set.

Rep 1 vs. 2	Trained			Untrained		
P4/P1 (g)						
Set	1	2	3	1	2	3
Repetition 1 mean	0.1532	0.1833	0.2004	0.1548	0.1920	0.1703
Repetition 2 mean	0.2074	0.2557	0.2423	0.1750	0.2102	0.2088
	p<0.05	p<0.05	p<0.05	NS	NS	p<0.05
P2/P3 (g)						
Set	1	2	3	1	2	3
Repetition 1 mean	0.2771	0.3268	0.3628	0.2580	0.2702	0.3036
Repetition 2 mean	0.3264	0.3702	0.3912	0.2725	0.3048	0.3196
	p<0.05	p<0.05	p<0.05	NS	NS	NS
PP (g)						
Set	1	2	3	1	2	3
Repetition 1 mean	0.4868	0.5835	0.6184	0.4399	0.4966	0.5272
Repetition 2 mean	0.5513	0.6388	0.6488	0.4605	0.5361	0.5862
	p<0.05	p<0.05	p<0.05	NS	NS	NS

Table 8. Paired T-tests of peak accelerations for P4/P1, P2/P3 and PP between repetition 1 and repetition 10 for each set.

Rep 1 vs. 10	Trained			Untrained		
P4/P1 (g)						
Set	1	2	3	1	2	3
Repetition 1 mean	0.1532	0.1833	0.2004	0.1548	0.1920	0.1703
Repetition 10 mean	0.2283	0.2481	0.2323	0.2096	0.2257	0.1935
	p<0.05	p<0.05	p<0.05	p<0.05	NS	p<0.05
P2/P3 (g)						
Set	1	2	3	1	2	3
Repetition 1 mean	0.2771	0.3268	0.3628	0.2580	0.2702	0.3036
Repetition 10 mean	0.3156	0.3647	0.3578	0.2976	0.3415	0.3253
	p<0.05	NS	NS	NS	p<0.05	NS
PP (g)						
Set	1	2	3	1	2	3
Repetition 1 mean	0.4868	0.5835	0.6184	0.4399	0.4966	0.5272
Repetition 10 mean	0.5502	0.6191	0.5948	0.5077	0.5478	0.5491
	p<0.05	NS	NS	p<0.05	NS	NS

Inter- set comparisons

We examined systematic inter-set differences by using the mean acceleration across all the repetitions for each set. We observed that that mean accelerations for peak P2/P3 values in set 1 were statistically lower ($p < 0.05$) in magnitude than both set 2 and set 3 for both trained and untrained groups (Figure 19 and 21 respectively). The mean PP magnitudes of set 1 were also found to be statistically lower ($p < 0.05$) than both set 2 and set 3 for both trained and untrained groups (Figure 17 and 19 respectively).

Peak Acceleration Slope

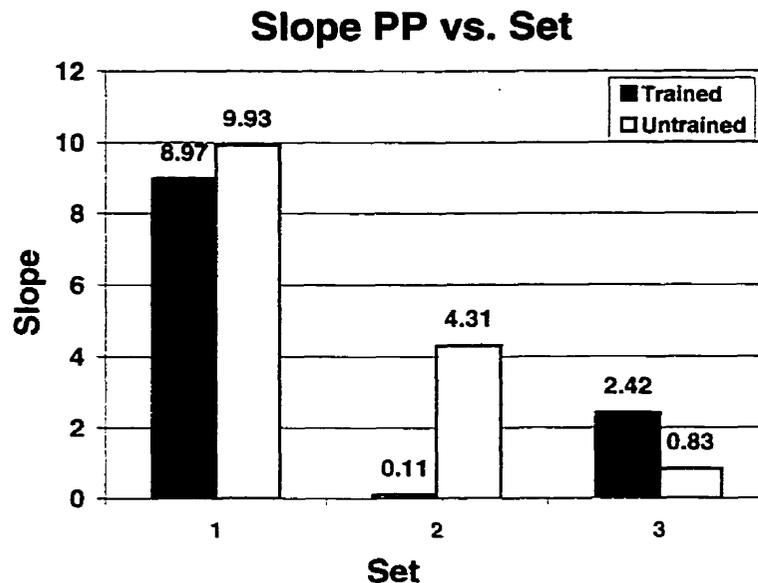


Figure 16. Slope of peak-to-peak acceleration across repetitions for trained and untrained groups for each continuous set.

A best-fit line was obtained by regressing the peak-to-peak acceleration (PP) with the repetitions number for each set. This was used as a measure of the change in magnitude of PP across each set. Figure 16 shows the change in slope that occurred across sets and between groups. We can observe that the first set has the steepest slope for both groups, and that the difference between the slopes of set 1 and 2 is greater than that between sets 2 and 3. A significant

linear relationship between slope and repetitions was observed for sets 1 and 2 for the untrained group, but only for set 1 in the trained group.

Peak Accelerations: Phase Magnitude Comparisons

Comparison between the magnitudes of the peak accelerations (P4/P1 with P2/P3) revealed that the P2/P3 magnitudes were significantly greater ($p < 0.05$) than those of the P4/P1 values in both the trained and the untrained groups for all sets (Figure 17 and 19 respectively).

Peak Accelerations

The peak accelerations (P4/P1, P2/P3 and PP & MM) were determined for each repetition and averaged across each group. The repetition averaged peak accelerations are shown in Figure 17 for the trained group and Figure 19 for the untrained group. Individual peak-to-peak (PP) acceleration values were plotted for each subject for each group (Figure 18 – trained and Figure 20 untrained) as an indicator of within group consistency (variability).

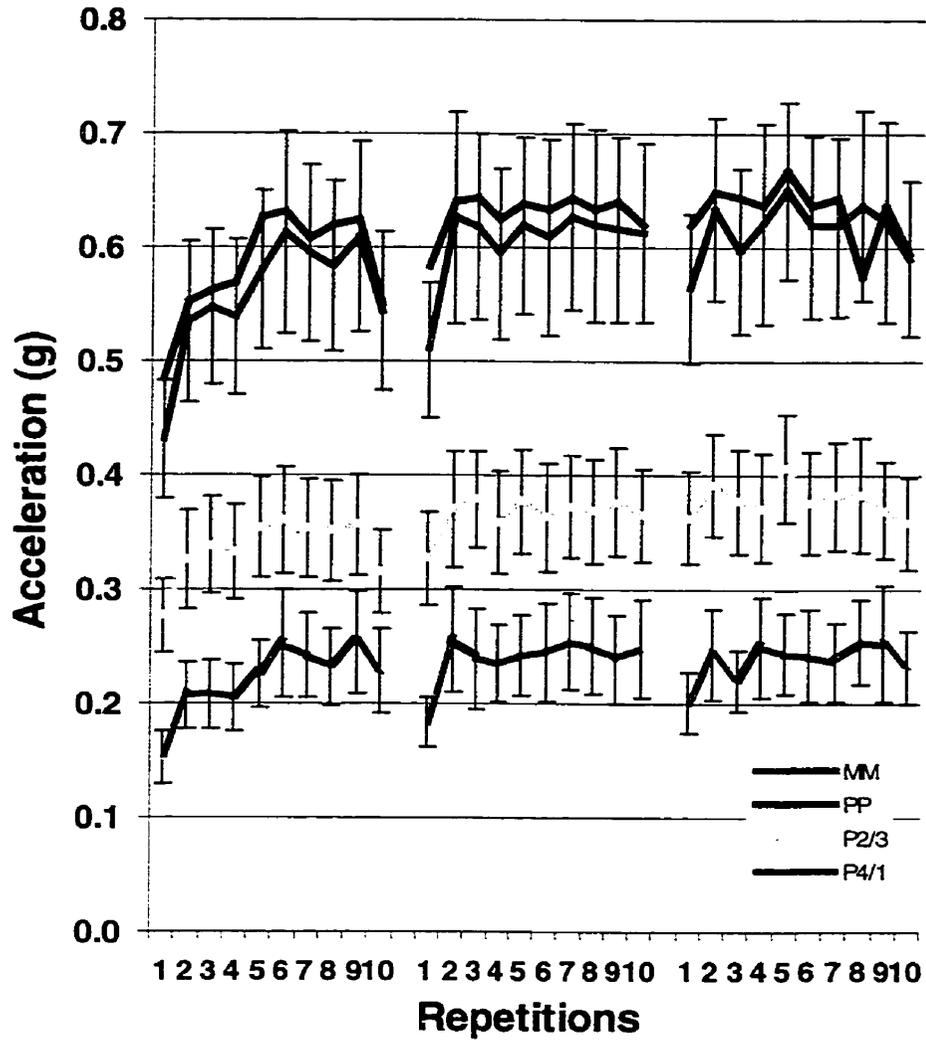


Figure 17. Mean peak acceleration for the trained group.

The individual PP accelerations were plotted for the trained group in Figure 18. It can be observed from this figure that there is a wider range of values for the trained group than the untrained group (Figure 20).

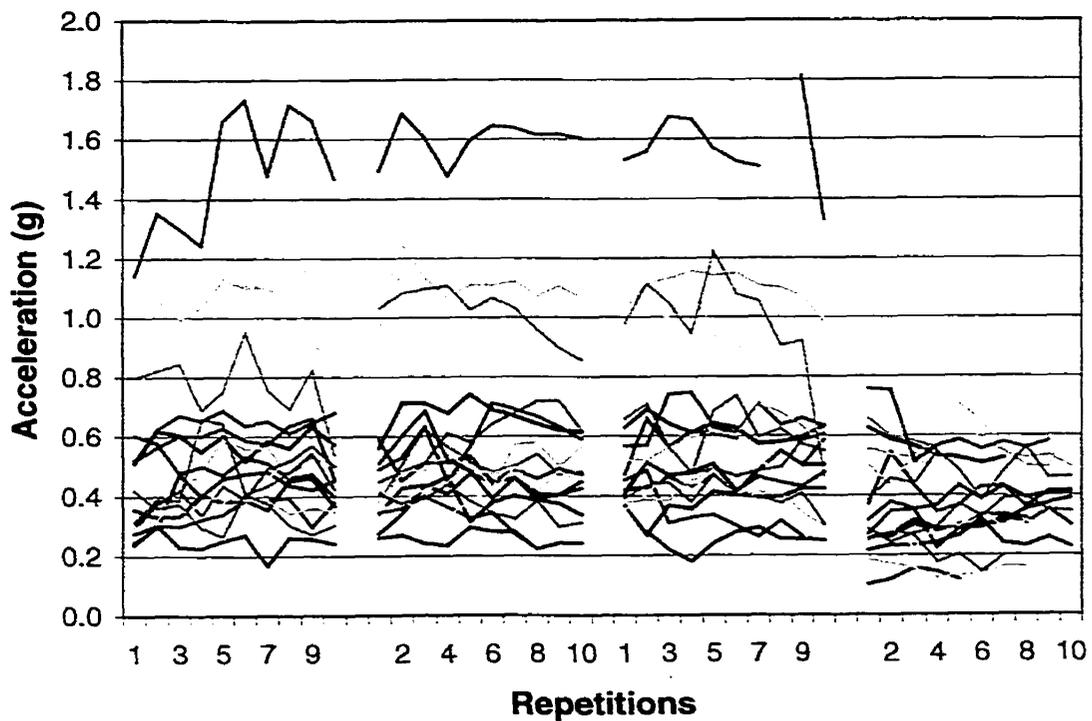


Figure 18. Plot of the peak-to-peak (PP) acceleration for each trained subject.

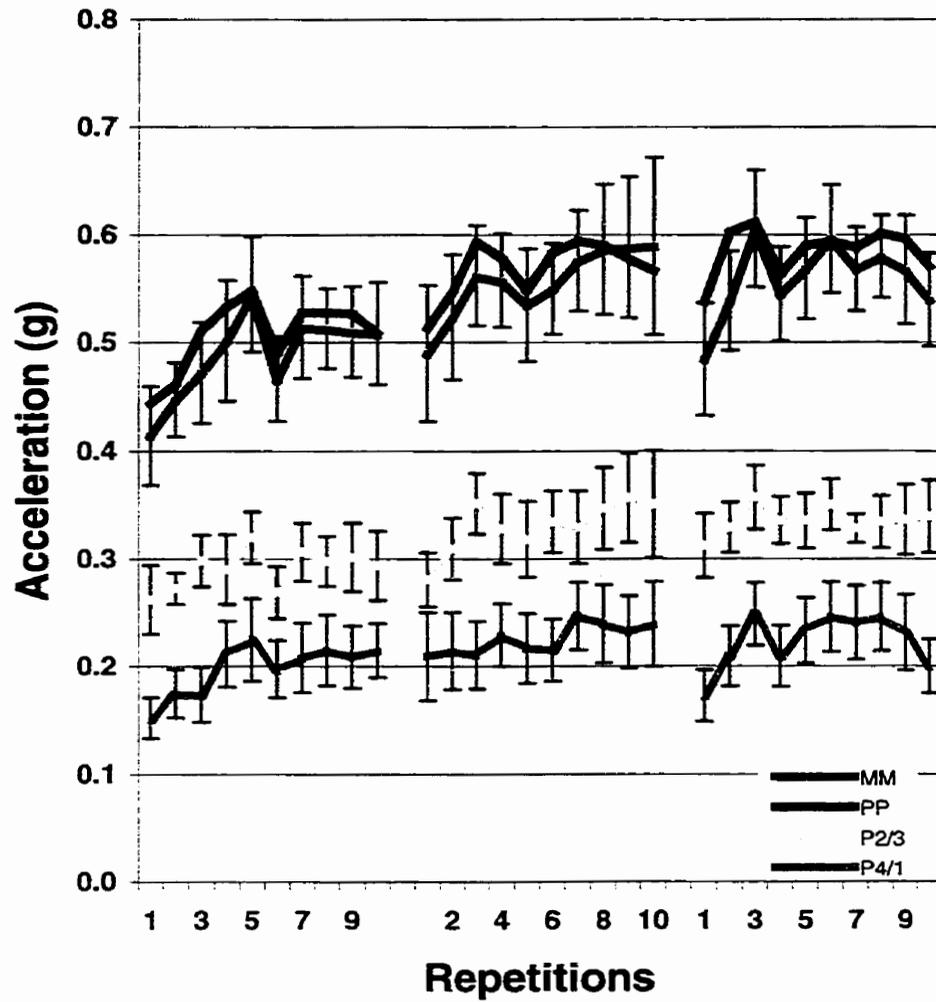


Figure 19. Mean peak acceleration for the untrained group.

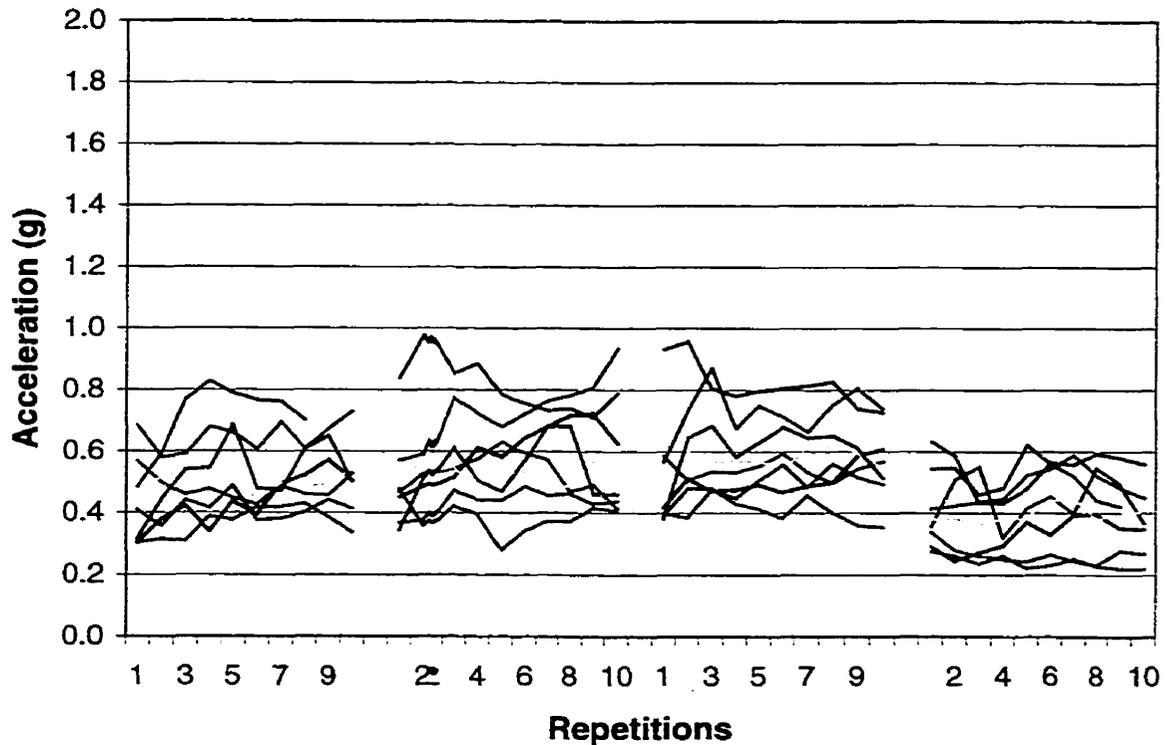


Figure 20. Plot of the peak-to-peak (P*P) accelerations for each untrained subject.

Correlation between P4/P1 and P2/P3

The relationship between the peak P4/P1 accelerations and the peak P2/P3 acceleration within each repetition was examined using scatter plots and correlation. Pearson-product moment correlation was performed between the peak P4/P1 and peak P2/P3 values for each group. The magnitude of the P4/P1 peak is well correlated with the peak P2/P3 in trained group ($r = 0.80$, $p < 0.05$). A scatter plot of the relationship is shown in Figure 21. The correlation was substantially lower in the untrained group ($r = 0.43$, $p < 0.05$), as can be discerned from the scatter plot shown in Figure 22.

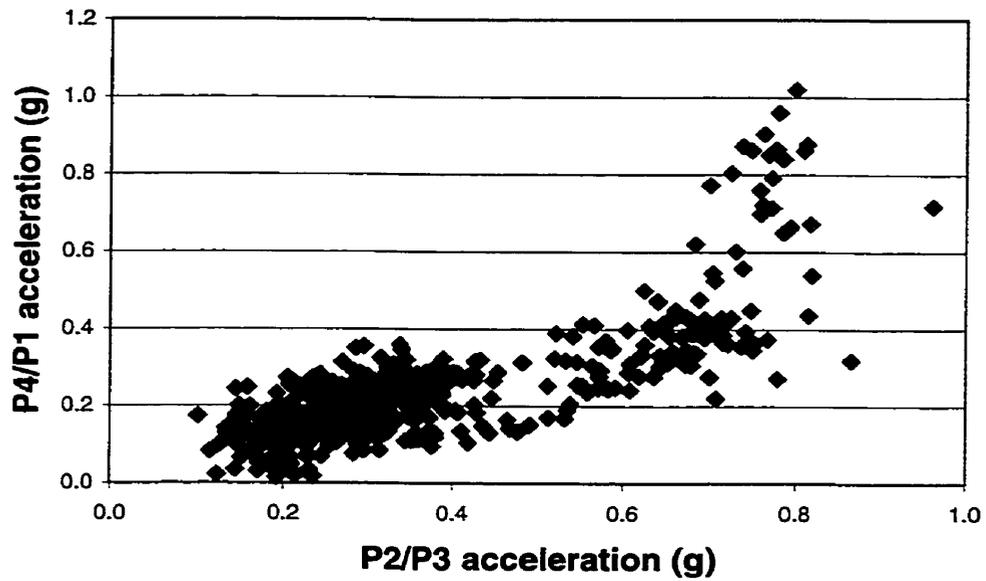


Figure 21. Scatter plot of peak P4/P1 accelerations versus peak P2/P3 accelerations for the trained group.

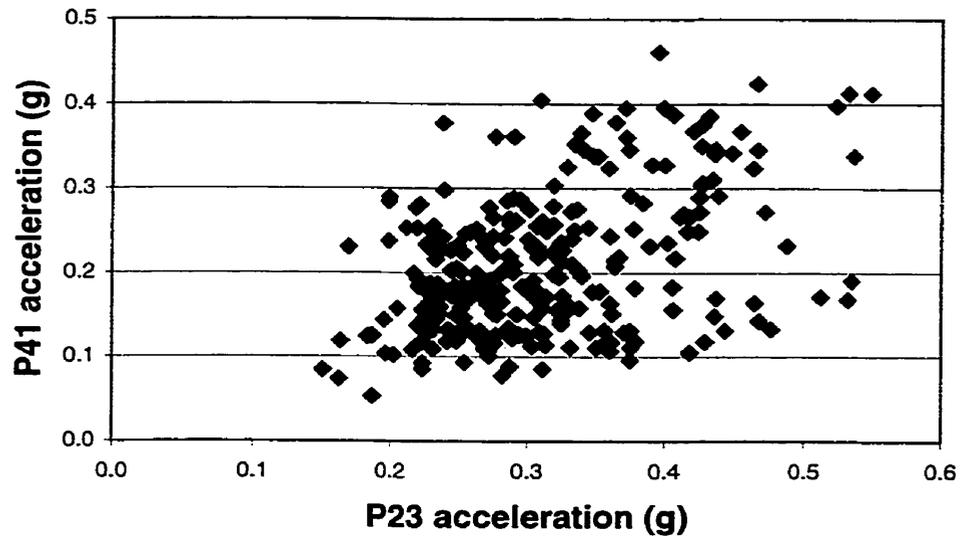


Figure 22. Scatter plot of peak P4/P1 accelerations versus peak P2/P3 accelerations in the untrained group.

Peak Accelerations during Continuous and Discontinuous Repetitions

The inclusion of a pause between repetitions and at the mid-repetition point in set 4 allowed the comparison between the two strategies on the basis of the magnitude of acceleration. It was observed that the PP acceleration magnitudes were substantially and statistically ($p < 0.05$) lower for the set with pauses than those performed continuously for both the trained (Figure 23) and untrained groups (Figure 24). The acceleration magnitudes were, on average, 36.6% lower for the trained group and 27.8% lower for the untrained group.

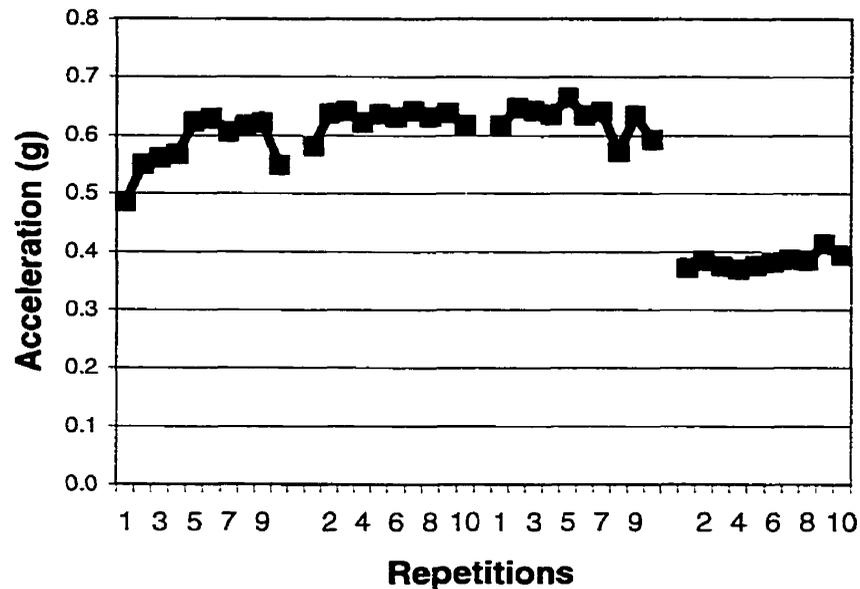


Figure 23. Mean peak-to-peak (PP) acceleration magnitude for sets 1-4 for the trained group.

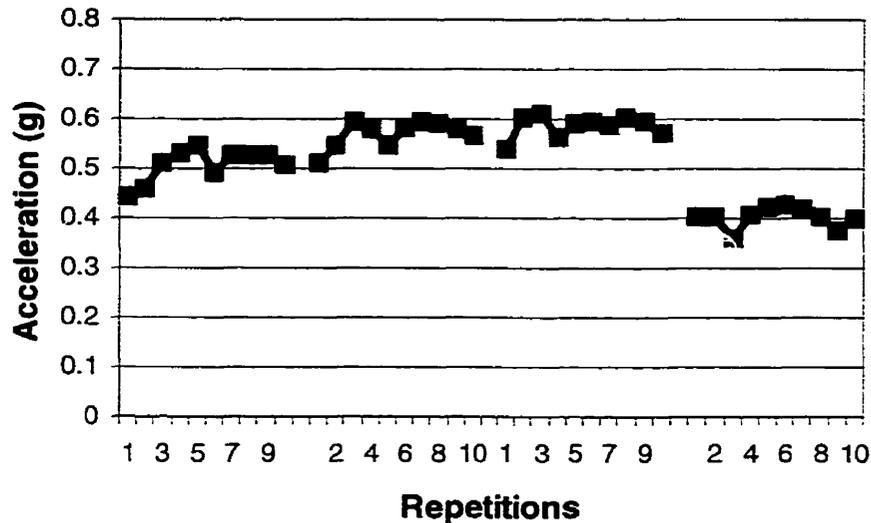


Figure 24. Mean peak-to-peak (PP) acceleration magnitude for sets 1-4 for the untrained group.

Summary of Results

There are 8 primary observations from this study that are significant to our understanding of acceleration and free weight resistance exercise. ■ There is a significant level of consistency in repetition duration that was self-selected by each of the subjects. This consistency was shown both across sets and between groups. ■ The repetition duration was significantly longer by 1.95 seconds in the fourth set that included two pauses. ■ The first repetition acceleration magnitude was significantly lower than the second for all sets in the trained group. ■ The peak-to-peak magnitudes of acceleration increase over repetitions in the first and second sets in the untrained group. This increase was observed in set 1 of the trained group. ■ The peak P4/P1 acceleration was found to be significantly lower than the absolute values of peak P2/P3 values for both sets and groups. ■ There was a correlation between the P4/P1 phase and the P2/P3 phase of each repetition for the trained group. ■ Even under these controlled conditions, the range of acceleration values was substantially larger for the trained group (1.6g) than those of the untrained group (0.7g). ■ Finally, the addition of momentary pauses resulted in a significant and substantial reduction in peak acceleration.

DISCUSSION

The primary objective of this study was to examine the inter-set and inter-repetition variation of acceleration profiles during a standardized free weight resistance exercise. This study is the first to document the within set and between set variations in acceleration in free weight exercise. The results of this study clearly indicate the importance of acceleration in loading during free weight exercise. As a secondary objective we also sought to examine the differences in acceleration between trained and untrained subjects performing the same standardized exercise. The comparison of the two groups revealed significant differences in the pattern, magnitude and consistency of acceleration during free weight exercise.

The inter-repetition analysis has shown that the peak-to-peak acceleration magnitude for the first repetition was significantly lower than the second for all sets in the trained group. This relationship was also observed in the untrained group but was only significant in the first set. The initial repetition of the movement is clearly different than the others in terms of the magnitude of the upward acceleration (P1). The P1 or upward acceleration is responsible for creation of the upward motion of the dumbbell. This upward dumbbell acceleration arises from concentric muscle contraction of the shoulder extensors and the elbow flexors. Interestingly, the second repetition has statistically higher upward acceleration magnitude than the first, which would indicate that the initial pull or lifting action upon the same mass (i.e. mass of the dumbbell, hand, forearm, and upper arm) would necessarily require higher peak instantaneous force generation by the muscles. The exact cause of this may lay in the fact that by the second repetition, there is a preceding P4 phase deceleration phase. In rehabilitation, sport and fitness fields this difference may or may not be desirable, but it certainly important to consider. For example to progressively increase the RJM about the joints involved in the action at each instant through the ROM from repetition 1 to repetition 2 may be beneficial to prevent injury. On the other hand, an Olympic weight lifter has only one repetition within which to achieve results. In everyday life, one is often called upon to lift an object one or more times and our

selection of movement acceleration may have great impact upon the ability to complete the task at all or without injury. These results enhance our understanding of acceleration control from repetition to repetition and highlight the need to consider acceleration in movement control.

In the first set of ten repetitions of the exercise, the peak acceleration magnitudes (PP and P4/P1) increased (illustrated in Figures 17 and 19) for both groups. This could arise from a progressive shift in neural activation strategy over the course of the set in order to counter the effects of fatigue or as an adaptation in coordination resulting from feed-forward sensory information. The trained group achieves stability in peak acceleration magnitudes by the 5th repetition in the first set and maintains this for the next two sets (except for the first repetition). The untrained group demonstrates progressive increases in peak-to-peak accelerations throughout the first 2 sets that stabilize in magnitude by the third set. This difference in acceleration reflects a difference in the neural control of movement between the two groups due to 1) experience with weight lifting or 2) neuromuscular fatigability. Certainly, the trained group had more experience in lifting weights (dumbbells in particular) and this could explain the more rapid adaptation of acceleration magnitude to stable values over sets, as well as the rapid adaptation in acceleration from repetition 1 to 2. Another possibility is that the untrained group had greater fatigability necessitating a progressive change in acceleration over sets. This second explanation is less favorable since the untrained group did stabilize the acceleration magnitude by the third set, and it is known that fatigue is progressive. These results have implications for estimating load during exercise. Given the same exercise parameters (sets, repetitions, weight, range of motion and even cadence) the acceleration dependent loading would be different for a novice weight trainer than an experienced weight trainer and may result in different rates of adaptation to a similar exercise program. This difference has implications for the type of motor units recruited for the exercise. Higher acceleration values and higher rates of acceleration development (jerk) may require selective recruitment of fast-twitch motor units. A study, which requires systematic variation in peak acceleration and records single motor units

using EMG, would be able to test this hypothesis. Further investigation is also required in assessing the short-term adaptation of acceleration patterns with training. We would predict that the novice weight trainers would progressively adapt to achieve greater stability in acceleration magnitude over repetitions and sets after some unknown period of weight training experience. Given that acceleration is controlled by the nervous system via the specific neuromuscular activation strategy employed for each repetition, one could speculate that the rate of adaptation may be rapid, consisting of only a few training sessions.

As expected, the 12 RM weight was significantly lower for the untrained group than the trained group. Interestingly, the number of sets to determine the 12 RM weight was not different between the two groups averaging nearly 2 sets for each group. We had expected that the untrained group might require additional sets to make a reasonable determination of the 12 RM value. Also, it is important to note that all subjects were capable of performing all 10 repetitions for each of the 4 sets using the 12 RM weight. We did not observe a progressive decrease in the number of repetitions that the untrained group could perform with each set. Similarly, we did not observe a slowing of the repetitions across the continuous repetition sets.

Each subject was permitted to control the duration of their own repetitions, up to an imposed limit of 5 seconds in the first three sets. No subjects reached this limit in the first three sets and only one subject had higher average repetition duration in the 4th set which included the imposed momentary pauses. The duration of repetitions did not significantly vary across sets or between groups in the first 4 sets. This shows that for this weight and type of exercise, that the weight training experience did not have a substantive effect on the cadence selected and performed. It is often suggested by practitioners and therapists that the reduction in the cadence (average velocity) of the movement will result in concomitant reduction in jerky (high acceleration) movements, that might ultimately lead to new injury or make an injury worse. The results of our study show that the repetition duration has very little variation between sets with a tendency to speed up over each set. Post-hoc, the relationship between

repetition duration and peak P4/P1 acceleration was examined. A significant negative correlation ($r=-0.74$, $p<0.05$) was observed indicating that as the self-selected repetition duration decreased (from 4s to 1 s) the peak P4/P1 acceleration increased (from 0.1 to 1.0 g). For continuous repetitions of the prone dumbbell row, it appears that the slower you perform the task the lower the peak upward acceleration in this controlled setting.

Examination of the raw plots of the individual peak acceleration values reveals a substantial range of acceleration values for the trained group. The range of peak P4/P1 accelerations was 1.6 g among trained subjects for an exercise with controlled range of motion, externally stabilized trunk, and controlled weight selection. This range of acceleration is substantial and would have an impact on loading. In order to illustrate this, a table (Table 9) was created using the "effective weight" method (Thompson and Bemben, 1998). In this method, Newton's Second Law is employed ($F=ma$, F is force, m is mass and a = linear acceleration) to compute the instantaneous "effective weight" of the dumbbell during the motion. This method is akin to watching a weigh scale while one performs squat actions. The "weight" of the person varies with the upward and downward accelerations, which actually translates into ground reaction forces being detected by the weigh scale that vary above and below body weight. Table 8 uses the minimum peak upward (P4/P1) acceleration from one subject of the trained group, the maximum peak upward acceleration observed for another trained subject, and a "maximal" peak acceleration recorded during a special trial where the subject was asked to perform the repetitions in an "all-out" fashion (See data in Appendix D). The average 12 RM mass (weight) was 12.87 kg for the trained group. Using this value for the computations, the peak acceleration values were adjusted to include "gravitational acceleration" by the addition of 1 g. The effective mass (weight) was derived as the product of actual mass and true acceleration, based upon $F=ma$. One can see that the instantaneous load represented by the effective mass varied substantially (1.6X increase) between subjects in the actual continuous sets under controlled circumstances due to acceleration. The 'all-out' trial reveals a doubling in instantaneous load! Clearly,

the differences in loading arising from acceleration are important to consider in exercise dose/response studies, as well as in practical settings. These differences may explain some of the variability in results that has been observed in resistance training studies, in which acceleration was not a controlled parameter.

Table 9 "Effective weight" calculations for a range of accelerations.

Peak P1 Acceleration	True Acceleration including 'g'	Average RM Mass (kg)	Effective Mass (kg)
0.1	1.1	12.87	14.1
0.8	1.8	12.87	23.2
1.26	2.26	12.87	29.1

This finding, illustrated by the effective weight computation, has implications for studies that employ training volume (e.g. Staron et al, 1994) as a quantification of an exercise program. Training volume is computed as sets X repetitions X weight. Based upon the Newtonian equations of motion, this indirect assessment of load (by weight alone) would only be sufficient when; 1) the same range of motion is maintained, 2) the same orientation of segments is maintained, 3) the same acceleration pattern is maintained, and 4) the same angular positions of each of the segments occur. This study has revealed specific limitations to the utility of this method. The use of training volume and weight as an estimate of load must be made in light of the impact of acceleration upon loading. For instance, the trainee may adopt a different control strategy to complete repetitions as fatigue sets in (i.e. they may jerk or drop the dumbbell at the beginning and end points of the ROM). The trainee may adopt compensatory movements and strategies possibly shifting some of the load to other muscle groups. These and other changes in motion may be influenced or be caused by several factors, but the key is that the acceleration patterns would be different. Thus, one of the problems with traditional methods of equating load to the weight is that it does not take into account the effects of motion, in particular the

acceleration dependant moment. The Newtonian Equation of Motion ($\sum M_{\text{joint}} = I\alpha$) states that the sum of all moments acting on a system about a joint sums to equal the product of the moment of Inertia (I in kgm^2) and angular acceleration (α in m/s^2). This relationship reveals that the RJM required or produced by a person is directly related to the angular acceleration of the system (body segments and free weights). The acceleration of the dumbbell is a primary contributor to the RJM generating requirements of the body based upon Newtonian equations of motion. Therefore, for any exercise movement, the quantification of the RJM is dependent upon knowledge and control of the acceleration pattern.

The range of peak P4/P1 acceleration values was considerably lower for the untrained group (0.7g untrained vs. 1.6 g trained) but this magnitude is still considerable. This difference between groups and individuals in range of acceleration could be related to issues of training in terms of goal oriented neuromuscular development. The subjects that had the higher values of accelerations were not only weight trained but competitive athletes, based upon post-hoc review of questionnaire data. Competitive athletes often train to maximize their ability to generate force and rate of rise of force, and this translates into high acceleration movement. Therefore, the chosen activation strategy was high acceleration oriented, as that is a focus for them in their sports and sport specific training. One trained subject on the other end of the range of acceleration magnitudes is a fitness consultant and general fitness enthusiast. The fitness consultant spends most of her time training for muscular development, joint and body stability. It could be argued that this subject over-emphasized her control of movement, possibly in anticipation of the intent of the study. This person also performed very slow repetitions 4.16 s compared with a group mean of 2.48 s.

Related to the issue of control of peak accelerations, is the relationship between the peak upward acceleration and peak downward acceleration within a single repetition. In order to lift the weight to a specific height and return the weight to the starting position, the area under the upward acceleration phases

(P4/P1) **must** mathematically equal the area under the downward acceleration phases. This does not require that the peak accelerations are equal, since the duration of each phase is also a factor in changing the area under the curve. In fact, the peak P4/P1 was found to be significantly lower in magnitude than the absolute value of the peak P2/P3. However, it was expected that these peaks (P4/P1 and P2/P3) would be proportional to each other. This was indeed the case for the trained group, which exhibited a strong linear relationship between the upward and downward accelerations. It is interesting to note that there is a non-linear element to the relationship at higher acceleration values. On the other hand, the untrained group exhibited a weak correlation between the peaks. This certainly could be explained by the lack of weight training experience of the untrained group, which could limit the within-repetition coordination.

As stated previously, we have shown that the peak upward accelerations (P4/P1) were significantly lower than the peak downward accelerations (P2/P3) during transition at the top of the ROM. A convincing explanation for this finding was not forthcoming. One possibility is that it may be due to a limitation of the musculature to develop tension (or the time to peak tension) and hence torque during the ascent phase. In contrast, higher accelerations may be achieved during P2/P3 since this corresponds to deactivation of the muscle rather than activation, especially for the P3 phase (see below). P1 corresponds to the initial pull upward on the dumbbell during the ascent phase and corresponds to concentric contraction of the prime movers. P4 consists of the final upward pull on the dumbbell, to slow it down to return it to the start of the ROM. P4 has the same sign as P1. The P4 phase corresponds to eccentric contraction of the prime movers. Both, the P4 and P1 peak accelerations were substantially lower than downward accelerations (P2/P3). P2 would correspond to a net downward acceleration on the dumbbell arising from concentric activation of the prime movers. Even though the prime movers are still shortening, they are imparting **less** acceleration to the dumbbell than the influence of gravity, resulting in a “deceleration” or slowing of the dumbbell to the top of the range of motion. P3 corresponds to the initial aspect of the descent phase, where the dumbbell

commences a controlled dropping motion. An uncontrolled drop of the dumbbell would result in a -1 g peak acceleration during P3 – like an object in free fall. Only a very small number of subjects ($n=3$, all trained) exhibited high P3 accelerations that approached -1 g and in those subjects only 1 repetition of 30 was close to free fall (-1 g). No actual free fall conditions were observed in any of the trials.

The addition of momentary pauses at the start of the motion and at the top resulted in a significant and substantial reduction in peak acceleration, as well as a significant increase in repetition duration. The duration increase would be expected because of the addition of two momentary pauses to each repetition. The significant reduction in peak-to-peak acceleration magnitudes was a more dramatic finding where the trained subjects showed a 37% decrease and the untrained a 28% decrease. This result reveals the impact of momentary pauses, which would have created a completely different loading profile (by magnitude and possibly by pattern) for the same exercise (as defined by the same movement pattern including ROM). The introduction of these momentary pauses separates the individual phases, which must have resulted in a change in neural activation strategy resulting in significantly lower peak-to-peak acceleration magnitude for each repetition. Indeed, the inclusion of a pause would make the eccentric contraction of the previous acceleration phase (P4) to be discontinuous with the concentric contraction required for the initiation of the next upward acceleration phase (P1). This would eliminate contribution of “stretch-shortening” effects (Komi 1992) to the force production of the muscles in the ongoing P1 concentric contraction. Conversely, the magnitude of the force potentiation from “stretch-shortening” effects, if any, during contiguous repetitions at this relatively slow movement frequency is unknown. This may be similar to the situation we observed for the lower peak P1 acceleration for the first repetition relative subsequent repetitions. In other words, the pauses create a “first repetition” situation for each of the repetitions in the set. Consistent with this observation is that in the fourth set, the peak-to-peak accelerations remained constant over all 10

repetitions. Further study is necessary to examine how the peak accelerations vary when the subject performs the task to fatigue failure.

CONCLUSION

From our results we can state that peak accelerations during a free weight resistance exercise vary between repetitions, sets, and subjects. From this it is possible to conclude that acceleration is a critical parameter in loading. Further, confirming our hypothesis, we have shown that the weight training experience influences the consistency, the magnitudes and pattern of acceleration, and hence loading during free weight exercise. We failed to support our hypothesis that there would be a progressive decrease in acceleration over successive repetitions and sets. In fact there was a progressive increase in acceleration over repetitions and sets for the untrained group (sets 1 and 2), and for set 1 in the trained group. This study has clearly demonstrated the utility of accelerometry in the study of resistance exercise.

RECOMMENDATIONS FOR RESISTANCE TRAINING

The results of this study permit some simple, guarded recommendations that need to be considered in resistance training in practice and in research.

- a) Acceleration dependent loading is important to consider for instruction of resistance exercise.
- b) Acceleration dependent loading should be considered in exercise progression, whereby the acceleration magnitude is modified from low to higher levels. The goals of the individual would be essential to consider in implementing acceleration progression.
- c) The ability to control or regulate the relationship between peak accelerations within a repetition is dependent upon the amount of experience in resistance training. This suggests that part of the early

learning process or adaptation of novice resistance trainers is improved coordination between the various phases within a repetition.

- d) Given the same weight and range of motion for an exercise, the addition of a small pause during an exercise (between repetitions and at mid-repetition) substantially changes the loading conditions. This is an important consideration for exercise instruction.
- e) Inter-individual variation in acceleration must be considered in design and implementation of resistance training programs.
- f) Understanding of acceleration in free weight resistance exercise may enhance our ability to become more efficient and effective in developing the neuromuscular system. Further, this understanding can be employed by therapists to guide patients to quicker recovery.

These recommendations should be tempered in light of the following caveats;

- 1) the possibility of a type II error due to a small sample size for the untrained group,
- 2) the ability to generalize the findings to males, and
- 3) the ability to generalize the findings to other exercises.

FUTURE STUDIES

This study is the first in a progression of studies, which is directed to the understanding of the exercise kinematics involving acceleration. Ultimately we are interested in human ability to control loads not only in exercise but also in everyday life. Further investigation of the effect of acceleration on loading is key to unlocking the mysteries behind the optimization of strength training and injury rehabilitation methods.

Additional studies need to be performed including examination of acceleration profiles during other resistance training exercises and for other forms of resistance training equipment. It is important to relate the magnitude of accelerations observed for each repetition to the magnitude of EMG activity of the prime movers. Further, it would be interesting to perform a longitudinal

training study of the effect of resistance training on acceleration profiles of novice weight trainers. These findings need confirmation in males. A comprehensive acceleration assessment should be performed which allows computation of instantaneous loading (RJM about major joints) for the prone dumbbell row. Further study is necessary to examine how the peak accelerations vary when the subject performs the task to fatigue failure.

REFERENCES

- Abernethy, P., Jurimae, J. (1996). Cross-sectional and longitudinal uses of isoinertial, isometric and isokinetic dynamometry. Medicine and Science in Sports and Exercise. 28, 1180-1187.
- Abernethy, P., Wilson G., Logan P.A. (1995) strength and power assessment: Issues controversies and challenges. Sports Medicine 19, 401-417.
- Adrian, M.J., & Cooper, J.M. (1998). Biomechanics of Human Movement. Iowa: Benchmark Press.
- Anderson, T. and Kearney, J.T. (1983). The effects of three resistance training programs on muscular strength and absolute and relative endurance, Research Quarterly in Exercise and Sport. 53, 1-7.
- Atha, J. (1981). Strengthening muscle. Exercise and Sport Science Review, 9, 1-73.
- Baechle T. (Ed.). (1994). Essentials of strength training and conditioning. (National Strength and Conditioning Association). Champaign: Human Kinetics.
- Bandy, W.D., Lovelace-Chandler, V., Mckitrick-Brandy, B. (1991). Adaptation to skeletal muscle to resistance training. Journal of Orthopedic and Sports Physical Therapy. 13, 226-229.
- Baratta R.V., Solomonow M., Best R., D'Ambrosia R. (1997). Force, velocity and energy dynamics of nine load-moving muscles. Medical Engineering and Physics, 19, (1), 37-49.
- Bompa T. O. (1996). Periodization of strength. Toronto: Veritas Publishing Inc.
- Chen K., Y., Sun M. (1997). Improving energy expenditure estimation by using a triaxial accelerometer. Journal of Applied Physiology, 83, (6), 2112-22.
- DeLorme, T.L. (1945). Restoration of muscle power by heavy resistance exercise. Journal of Bone and Joint Surgery, 27, 645-667.
- Dudley, G. A., Tesch, P. A., Miller, B. J., & Buchanan, P. (1991). Importance of eccentric actions in performance adaptations to resistance training. Aviation, Space, and Environmental Medicine, 62, 543-550.

- Enoka R. M. (1994). Neuromechanical basis of kinesiology (2nd ed.). Champaign, Human Kinetics.
- Fleck, S.J. & Schutt, R.C. (1985). Types of strength training. Clinics in Sports Medicine 4, 150-169.
- Fleck, S.J., & Kraemer, W.J. (1997). Designing resistance training programs (2nd ed.). Champaign: Human Kinetics Books.
- Gallasch E., Kenner T. (1997). Characteristics of arm microvibration recorded on an accelerometer. European Journal of Applied Physiology, 75,(3), 226-32.
- Gransberg, L., & Knutsson, E. (1983). Determination of dynamic muscle strength in man with acceleration controlled isokinetic movements. Acta Physiologica Scandinavica, 119, 317-320.
- Harman, E., (1993). Strength and power: a definition of terms. Journal of Strength and Conditioning, 15,18-20.
- Harre, D. (Ed.) (1982). Principles of sports training: Introduction to the theory and methods of training. East Berlin: Sportverlag.
- Hay, J.G., Andrews, J.G., Vaughan, C.L. (1980). The influence on external load on the joint torques exerted in a squat exercise. In J.M. Cooper & B. Haven (Eds.), Proceedings of the Biomechanics symposium (pp. 286-293). Indiana University: Indiana State Board of Health.
- Herren, R., Sparti, A., Aminian, K., Schutz, Y. (1999). The prediction of speed and incline in outdoor running in humans using accelerometry. Medicine and Science in Sports and Exercise. 7, 1053-1059.
- Hoeger, W.W.K., Hopkins, D.R., Barette, S.L. (1990). Relationship between repetitions and selected percentages of one repetition maximum: A comparison between trained and untrained males and females. Journal of Applied Sport Science Research. 4, 47-54.
- Hortobagyi T., Katch F. I., LaChance P. F. (1991). Effects of simultaneous training for strength and endurance on upper and lower body strength and running performance. Journal of Sports Medicine and Physical Fitness, 31, 20-30.

Hortobagyi, T., Katch, F., LaChance, P. (1989). Interrelationships among various measures of upper body strength assessed by different contraction modes. European Journal of Applied Physiology. 58, 749-755.

Howley E. T., & Franks B. D. (1997). Health fitness instructor's handbook (3rd ed.). Champaign: Human Kinetics.

Kisner, C., Colby, L.A., (1996). Therapeutic exercise: Foundations and techniques. Philadelphia. PA: F.A. Davis Company.

Komi P.V. (Ed.). (1992). Strength and Power in Sport. Oxford: Blackwell Scientific Publications.

Lander, J. (1985). Maximums based on reps. National Strength and Conditioning Association Journal. 6, 60-61.

Lemelin, S., J., (1995). An EMG analysis of the muscles involved in the incline and supine bench press. University of Manitoba, July.

Lieber R.L. (1992). Skeletal muscle structure and function: implications for rehabilitation and sports medicine. Maryland: Williams & Wilkins.

Logan, P., Fomasiero, D., Abernethy, P., Lynch, K. Protocols for assessment of isoinertial strength. In Gore, C. J. (Ed.). (2000). Physiological tests for elite athletes (pp. 200-221) Australian Sports Commission. Windsor: Human Kinetics

MacDougall J. D., Wenger H. A., & Green H. J. (1991). Physiological testing of the high-performance athlete (2nd ed.). Champaign: Human Kinetics.

Mayhew, J.L., Ball, T.E. and Bowen, J.C. (1992). Prediction of bench press lifting ability from submaximal repetitions before and after training. Sports Medicine of Training and Rehabilitation. 3, 195-201.

McArdle, W.D., Katch, F. I., & Katch, V.L. (1991). Exercise physiology: energy, nutrition, and human performance (4th ed.). Maryland: Williams & Wilkins.

McDonagh, M.J., & Davies, C.T. (1984). Adaptive response of mammalian skeletal muscle to exercise with high loads. European Journal of Applied Physiology, 52, 2, 139-55.

Mendelson, L.S; Peckham, P.H; Freehafer-, A.A; Keith, M.W. 1988. Intraoperative assessment of wrist extensor muscle force. Journal of Hand Surgery America. 1988 Nov; 13(6), 832-6

Murphy, A.J., Wilson, G.L. and Prior, J.F. (1994). Use of the isoinertial force mass relationship in the prediction of dynamic human performance. European Journal of Applied Physiology. 69, 250-257.

Myers, A. (1992). The clinical swiss army knife; Empirical evidence on the validity of IADL functional status measures. Medical Care. 30, 5, 96-111.

Narici, M., Bordini, M., & Cerretelli, P. (1991). Effect of aging on human adductor pollicis muscle function. Journal of Applied Physiology, 71, 1227-1281.

Ng A.V., Kent-Braun J.A., (1997). Quantitation of lower physical activity in persons with multiple sclerosis. Medicine and Science in Sports and Exercises, 29, 4, 517-23,

Pardy, W. Strength training In Basmajian, T.V., Nyberg, R., (Eds.) (1993). Rational Manual Therapies. Williams & Wilkins, Baltimore.

Perrin, D.H. (1954). Isokinetic exercise and assessment. Champaign, IL: Human Kinetics.

Reiser R. F., Smith S. L., & Rattan R. (1996). Science and technology to enhance weightlifting performance: the Olympic program. Strength and Conditioning, 18, 4, 43-51.

Robertson, D., G., E. (1997). Introduction to biomechanics for human motion analysis. Waterloo: Waterloo Biomechanics.

Sale, D., MacDougall, D. (1981). Specificity in strength training: a review for the coach and athlete. Canadian Journal of Applied Sport Science, 6, 2, 87-92.

Sale, D.G. (1991). Testing strength and power. In: MacDougall, J. Wenger, H. and Green, H. (eds) Physiological Testing of the High Performance Athlete. Champaign, Illinois: Human Kinetics, 21-106.

Sewall, L.P. and Lander, J.E. (1991). The effects of rests on maximal efforts in squat and bench press. Journal of Applied Sport Science Research. 5, 96-99.

Staron, R.S., Karapondo, D.L., Kraemer, W.J., Fry, A.C., Gordon, S.E., Falkel, J.E., Hagerman, F.C., Hikida, R.S. (1994). Skeletal muscle adaptations during the early phase of heavy-resistance training in men and women. Journal of Applied Physiology, 76, 631-640.

Stone M. H., & Borden R. A. (1997). Modes and methods of resistance training. Strength and Conditioning, 19, 4, 18-24.

Thompson, C.J., Bembien, M.G. (1998). Reliability and comparability of the accelerometer as a measure of muscular power. Medicine and Science in Sports and Exercise, 6, 897-902.

Tihanyi, J., Apor. P. and Fekete, G. (1982). Force-velocity power characteristics and fiber composition in human knee extensor muscles. European Journal of Applied Physiology. 48, 331-343.

Tyska, M.J; Dupuis, D.E; Guilford, W.H; Patlak, J.B; Waller, G.S; Trybus, K.M; Warshaw, D.M.; Lowey, S. 1999 Two heads of myosin are better than one for generating force and motion Proc-Natl-Acad-Sci-U-S-A.1999 Apr 13; 96(8), 4402-7

U.S. department of Health and Human Services. Physical Activity and Health: A report of the Surgeon General. Surgeon General Report. Atlanta, GA: Department of Health and Human Services Centers for disease Control and Prevention. National Center for Chronic Disease Prevention and Health Promotion. 1996.

Vandervoort, A.A., & McComas, A.J. (1986). Contractile changes in opposing muscles of the human angle joint with aging. Journal of Applied Physiology, 61, 361-367,

Verplaetse, C., (1999). Inertial proprioceptive devices: Self-motion-sensing toys and tools. IBM Systems Journal 35, NOS 3&4, 639-650.

Viitasalo, J.T. (1985a). Effects of training on force-velocity characteristics. In:D.A. Winter, R.W. Norman, R.P. Wells et al. (eds.) Biomechanics IX-A. Champaign, Illinois: Human Kinetics 91-95.

Viitasalo, J.T. (1985b). Measurement of force velocity characteristics for sportsmen in field conditions. In: D.A. Winter, R.W. Norman, R.P. Wells et al. (eds) Biomechanics IX-A. Champaign, Illinois: Human Kinetics 91-95.

Viitasalo, J.T. and Auro, O. (1984). Seasonal fluctuations of force production in high jumpers. Canadian Journal of Applied Sport Science. 90(4), 209-213.

Weir, J.P., Wagner, L.L. and Housh, T.J. (1994). The effects of rest interval length on repeated maximal bench presses. Journal of Strength and Conditioning Research. 8, 58-60.

Wilson, G.J., Lyttle, A.D., Ostrowski, KJ. And Murphy, A.J. (1995). Assessing dynamic performance: A comparison of rate of force development tests. Journal of Strength and Conditioning Research. 9(3), 176-181.

Winter, D.A., Wells, R.P., & Orr, G.W. (1981). Errors in the use of isokinetic dynamometers. European Journal of Applied Physiology, 46,397-408.

Young W. B., Jenner A., & Griffiths K. (1998). Acute enhancement of power performance from heavy load squats. Journal of Strength and Conditioning Research, 12 , 2, 82-84.

Zatsiorsky, V. M. (1995). Science and practice of strength training. Champaign: Human Kinetics.

Zedka, M., & Prochazka, A. (1997). Phasic activity in the human erector spinae during repetitive hand movements. Journal of Physiology, 504, (3), 727-734.

APPENDIX A: SCREENING ASSESSMENT & QUESTIONNAIRE

The effect of sets and repetitions on acceleration in free weight resistance exercise.

University of Manitoba 1999

Contact: Dr. Dean Kriellaars
787-2289



THE UNIVERSITY OF
MANITOBA
FACULTY OF MEDICINE
School of Medical Rehabilitation

Name _____

Date _____

Date of Birth _____ (mm/day/yr.)

Height (cm) _____

Body Mass (kg) _____

Which arm would you throw a ball with? R or L

Have you participated in any elite/competitive sports in the past 2 years?

If so, specify _____

Exercise history:

1. Do you exercise regularly? _____
2. What type of activity do you participate in? _____

3. How long are your workouts? _____
4. How frequently do you exercise? _____
5. Have you been exercising for less than three months? _____
6. Do you perform the bent over dumbbell row in your training? _____

7. Do you perform any other latissimus dorsi exercise in your training (if yes please specify)? _____

8. Have you ever injured the arm you throw a ball with? If yes, specify type of injury?

9. _____

10. Have you ever injured the shoulder of the arm you throw a ball with? If yes, specify type of injury. _____

11. Do you have any restriction in movement of your "throwing" arm?

12. Do you have any cardiovascular problems (e.g. dizziness, high blood pressure, pain in chest) or any other medical conditions (e.g. arthritis) which might affect your ability to participate in the study?

13. Are you currently pregnant or breastfeeding? _____

14. Do you currently have any injury to your non-dominant arm?

15. Have you ever-used performance enhancing drugs? If yes, please specify types of drugs used, dosage of drugs consumed and period of time spent using each drug?

APPENDIX B: PARAPHRASE

The effect of sets and repetitions on acceleration in free weight resistance exercise.

University of Manitoba 1999

Contact: Dr. Dean Kriellaars
787-2289



THE UNIVERSITY OF
MANITOBA
FACULTY OF MEDICINE
School of Medical Rehabilitation

Paraphrase

Strength training is an important component in both athletic performance and rehabilitation. Practitioners commonly prescribe progressive resistance exercise programs to develop strength. Little is known about how the control of movement during exercise influences the effort required by the individual. Differences in resistance can occur simply due to the way in which the exercise is performed. We propose to use a special device, called an accelerometer, to measure the variation in resistance during a simple exercise task. In order to better prescribe, assess and monitor training programs a better understanding of how the resistance changes during exercise is needed.

PROCEDURE

All of the subjects will be recruited by word of mouth. As a subject in this study, you will be asked not to partake in any form of exercise other than your regular daily living activities on the day of the testing and for 2 days prior to the day of testing. You will undergo a simple screening assessment/questionnaire. No risk or discomfort is associated with this procedure. After the screening, you will perform two strength tests involving a dumbbell exercise. Electrodes will be attached to your muscles to record the electrical activity of the muscles involved in the exercise. There is no risk or discomfort associated with this recording. The exercise is called a 'prone dumbbell row' and is used to measure strength about your shoulder and arm. You will be provided with familiarization and instruction on how to perform this exercise. The total time for testing will not exceed 2 hours.

The first strength test is used to determine of the maximum amount of weight that you can lift 12 times performing the dumbbell row. This is called your 12 Repetition Maximum (RM) load or resistance. It commonly takes 2-5 attempts to determine this 12 RM load. With each attempt the weight will be increased until you reach the load which you can only lift 12 times (with proper technique). You will be provided 2 minutes rest between each attempt. For the first attempt, the weight will be set using a conservative estimate provided by you. You will have a 5-minute rest period after this strength test.

The second strength test will require you to complete 4 sets of 10 repetitions of the dumbbell row exercise with the 12 RM load determined in the first strength test. You will have 60 seconds rest between each of the four sets of 10 repetitions.

The strength tests described above will be stopped:

1. If you wish to stop for any reason,
2. If you exhibit signs of pain or severe discomfort, and
3. If you do not use proper form.

Risks

The risks associated with the strength tests are minimal including;

A. After maximal exertion you may experience some minor discomfort in the muscles involved in the exercise, which begins 12-24 hours after the exercise and may last up to four days after the test. This is a normal consequence of exercise and will resolve on its own.

B. A certain amount of minor discomfort may be associated during the test (as with any form of exercise). However, if obvious pain arises at any time during the test, the test will be discontinued.

C. Although there have not been any published reports of muscle damage during these tests, there is a small possibility that a tear in the muscle may occur. Similar tests have been performed on athletes and untrained subjects about different joints, with and without pathology, and even after surgery without documented damage to the muscles.

You will not be identified in any published report of the results of this study. You will not be paid to participate in this project, your participation is voluntary and you are free to withdraw at any time and for any reason. You are not responsible for any costs directly related to the study.

Any and all information provided for this study will be kept confidential. If you have any questions or do not understand any aspect of this form, please contact,

Dr. Dean Kriellaars
School of Medical Rehabilitation
University of Manitoba
787-2289

APPENDIX C: CONSENT FORM

The effect of sets and repetitions on acceleration in free weight resistance exercise.
University of Manitoba 1999

Contact: Dr. Dean Kriellaars
787-2289



THE UNIVERSITY OF
MANITOBA
FACULTY OF MEDICINE
School of Medical Rehabilitation

The effect of sets and repetitions on acceleration in free weight resistance exercise.
Consent Form

I have read the paraphrase and understand the nature of the study including the potential benefits and risks. I have satisfied any questions that I may have had with respect to this study. I agree to participate in this study and abide by the procedural requirements. I understand that I will not receive compensation for my participation in this study.

I understand that I may withdraw from the study at any time and that I will not be identified in any publications arising from this study. The signing of this document does not waive my legal rights.

Subject (print name) _____ Date _____

Subject (sign) _____

Witness (print name) _____ Date _____

Witness (sign) _____

Investigator (print name) _____ Date _____

Investigator (sign) _____

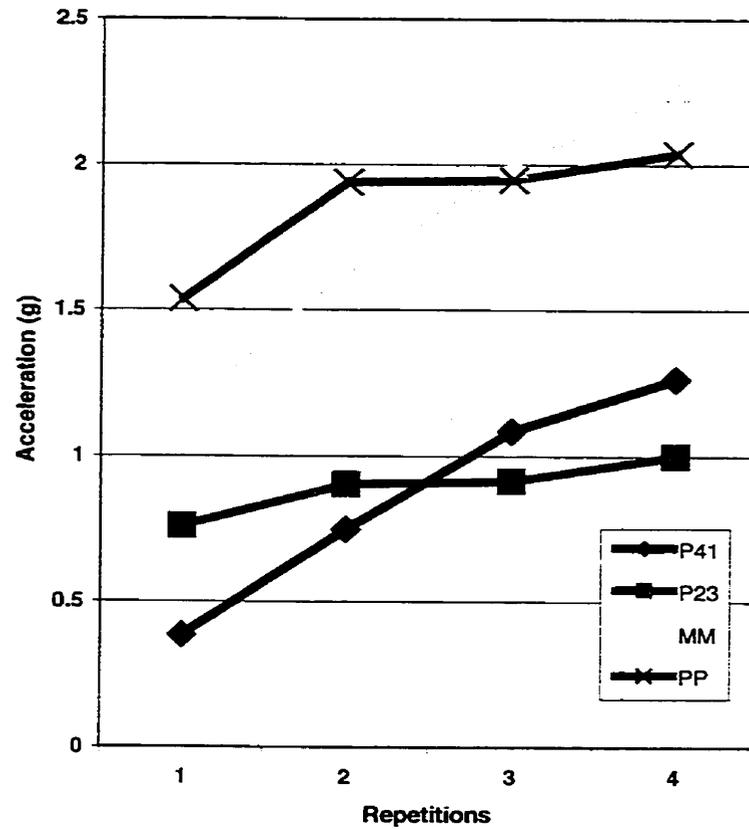
APPENDIX D: EXAGGERATED ACCELERATION PROFILE

Figure 25. Peak accelerations for one subject performing a set of 4 repetitions in a 'maximal effort' manner.