Edith Cowan University

2007

Assessment and enhancement of lower extremity power of athletes

Naruhiro Hori
Edith Cowan University

Recommended Citation

Hori, N. (2007). *Assessment and enhancement of lower extremity power of athletes.*
https://ro.ecu.edu.au/theses/36

ASSESSMENT AND ENHANCEMENT OF LOWER EXTREMITY POWER OF ATHLETES

A thesis submitted for the degree of
Doctor of Philosophy
August 2007
by
Naruhiro Hori

School of Exercise, Biomedical and Health Sciences
Edith Cowan University
Joondalup, Western Australia

USE OF THESIS

ABSTRACTS

STUDY 1: RELIABILITY OF PERFORMANCE MEASUREMENTS DERIVED FROM GROUND REACTION FORCE DATA DURING COUNTERMOVEMENT JUMP AND INFLUENCE OF SAMPLING FREQUENCY

Force platforms are used extensively to measure force and power output during countermovement jump (CMJ). The purpose of this study was to examine measurement reliability and validity of commonly used performance measurements derived from ground reaction force (GRF)-time data during CMJ and the influence of sampling at different frequencies. Twenty four subjects performed two trials of CMJ on a force platform, and GRF-time data were sampled at a rate of 500 Hz. Data obtained at 500 Hz was considered as a reference, and then data were re-sampled at 400, 250, 200, 100, 50 and 25 Hz using interpolation. Commonly used power, force, and velocity performance measures were obtained from GRF-time data. Reliability was assessed by intra-class correlation coefficient (ICC) and coefficient of variance (CV) between the two trials within the session. Peak power, peak force and peak velocity were highly reliable across all sampling frequencies (ICC = 0.92-0.98, CV = 1.3-4.1%). Percentage differences from 500 Hz reference values ranged from -0.85 to 0.20% at 400 Hz, -1.88 to 0.89% at 250 Hz, -1.80 to 1.31% at 200 Hz, -3.63 to 3.34% at 100 Hz, -11.37 to 6.51% at 50 Hz, and -13.17 to 9.03% at 25 Hz. In conclusion, peak power, force and velocity measurements derived from GRF to assess leg extensor capabilities are reliable within a test session except for peak rate of force development and time to peak force. With regard to sampling frequency, scientists and practitioners may consider sampling as low as 200 Hz depending on the purpose of measurement since the percentage difference is not markedly enlarged until frequency is 100 Hz or lower.

STUDY 2: COMPARISON OF FOUR DIFFERENT METHODS TO MEASURE POWER OUTPUT DURING THE HANG POWER CLEAN AND THE WEIGHTED JUMP SQUAT

Measurement of power output during resistance training is becoming ubiquitous in strength and conditioning programs but there is great variation in methods used. The main purposes of this study were (a) to compare the power output values obtained from four different methods, and (b) to examine the relationships between these values. Male semiprofessional Australian rules football players (n = 30) performed hang power clean and weighted jump squat while ground reaction force (GRF)-time data and barbell displacement-time data were sampled simultaneously using a force platform and a linear position transducer attached to the barbell. Peak and mean power applied to the barbell was obtained from barbell displacement-time data (Method 1). Peak and mean power applied to the system (barbell + lifter) was obtained from three other methods: using GRF-time data (Method 2), using barbell displacement-time data (Method 3) and using both barbell displacement-time data and GRF-time data (Method 4). The peak power values (W) obtained from Methods 1, 2, 3 and 4 were (mean ± SD); 1644 ± 295, 3079 ± 638, 3821 ± 917, and 4017 ± 833 in hang power clean, and 1184 ± 115, 3866 ± 451, 3567 ± 494, and 4427 ± 557 in weighted jump squat. There were significant differences between power output values obtained from Method 1 vs. Methods 2, 3 and 4 as well as Method 2 vs. Methods 3 and 4. The power output applied to the barbell and that applied to the system was significantly correlated (r = 0.65 – 0.81). As a practical application, it is important to understand the characteristics of each method, and consider how power output should be measured during the hang power clean and the weighted jump squat.

STUDY 3: DOES PERFORMANCE OF HANG POWER CLEAN DIFFERENTIATE PERFORMANCE OF JUMPING, SPRINTING, AND CHANGING OF DIRECTION?

The primary purpose of this study was to investigate whether the athlete who has high performance in hang power clean, a common weightlifting exercise, has high performances in sprinting, jumping and changing of direction (COD). As the secondary purpose, relationships between hang power clean performance, maximum strength, power and performance of jumping, sprinting and COD were also investigated. Twenty-nine semiprofessional Australian Rules football players (age, height, and body mass [mean ± SD]: 21.3 ± 2.7 yr, 1.8 ± 0.1 m, and 83.6 ± 8.2 kg) were tested for one repetition maximum (1RM) hang power clean, 1RM front squat, power output during countermovement jump with 40 kg barbell and without external load (CMJ), height of CMJ, 20 m sprint time, and 5-5 COD time. The subjects were divided into top and bottom half groups ($n = 14$ for each group) based on their 1RM hang power clean score relative to body mass, then measures from all other tests were compared using one-way analyses of variance. In addition, Pearson's product moment correlations between measurements were calculated among all subjects ($n = 29$). The top half group possessed higher maximum strength ($p < 0.01$), power ($p < 0.01$), performance of jumping ($p < 0.05$) and sprinting ($p < 0.01$). However, there was no significant difference between groups in 5-5 COD time possibly due to important contributing factors other than strength and power. There were significant correlations between most of, but not all combinations of performances of hang power clean, jumping, sprinting, COD, maximum strength and power. Therefore, it seems likely there are underlying strength qualities that are common to the hang power clean, jumping and sprinting.

STUDY 4: COMPARISON OF WEIGHTED JUMP SQUAT TRAINING WITH AND WITHOUT ECCENTRIC BRAKING

The purpose of this study was to investigate the effect of weighted jump squat training with and without eccentric braking. Twenty male subjects were divided into two groups (n = 10 per group), Non-Braking Group and Braking Group. The subjects were physically active, but not highly trained. The program for Non-Braking Group consisted of 6 sets of 6 repetitions of weighted jump squats without reduction of eccentric load for 8 weeks. The training program for Braking Group consisted of the same sets and repetitions, but eccentric load was reduced by using an electromagnetic braking mechanism. Jump and reach, countermovement jump, static jump, drop jump, one repetition maximum half squat, weighted jump squat, isometric/isokinetic knee extension/flexion at several different positions/angular velocities were tested pre- and post- training intervention. Non-Braking Group exhibited greater improvement in peak torque during isokinetic concentric knee flexion at 300°/s (Non-Braking Group: [mean ± S.D.] 124.0 ± 22.6 Nm at pre- and 134.1 ± 18.4 Nm at post-training, and Braking Group: 118.5 ± 32.7 Nm at pre- and 113.2 ± 26.7 Nm at post-training). Braking Group exhibited superior adaptations in peak power relative to body mass during weighted jump squat (Non-Braking Group: [mean ± S.D.] 49.1 ± 8.6 W/kg at pre- and 50.9 ± 6.2 W/kg at post-training, and Braking Group: 47.9 ± 6.9W/kg at pre- and 53.7 ± 7.3W/kg at post-training). It appears that power output in relatively slow movement (weighted jump squat) was improved more in the Braking Group, however strength in high velocity movements (isokinetic knee flexion at 300°/s) was improved more in Non-Braking Group. This study supports load and velocity specific effects of weighted jump squat training.

DECLARATION

I certify that his thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(ii) contain any material previously published or written by another person except where due reference is made in the text; or

(iii) contain any defamatory material.

I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis as required.

29/8/2007

Naruhiro Hori

ACKNOWLEDGEMENTS

First of all, I wish to thank the following people who have greatly assisted me.

Dr. Robert U. Newton and **Dr. Kazunori Nosaka** for their supervision.

All of my subjects for their participation.

Co-investigators (**Dr. Michael R. McGuigan**, **Mr. Warren A. Andrews**, **Mr. Dale W. Chapman**, and **Mr. Naoki Kawamori**) and laboratory technicians (**Ms. Nadija Vrdoljak** and **Mr. Jonathon P. Green**) for their assistance.

Dr. Michael H. Stone at East Tennessee State University, for introducing Dr. Robert U. Newton to me.

Mr. Steven R. Lawrence, **Mr. Martin FitzSimons**, **Mr. Gilman J. Barnitt**, and **Mr. Gregory T. Morgan** at Western Australian Institute of Sport, **Mr. Brendyn B. Appleby** at Western Force, **Mr. Jason P. Duff** at Hockey Australia/Australian Institute of Sport, **Mr. Jack Walls** at Midland Pythons Weightlifting Club, **Mr. Brendan E. Kennedy** at Wesley College, **Dr. Andrew C. Fry** at The University of Kansas, **Dr. Lawrence W. Weiss**, **Dr. Brian K. Schilling**, and **Mr. Edwin D. Cantler Jr.** at the University of Memphis, **Mr. Loren Z. F. Chiu** at University of Southern California, **Dr. Isao Okuda** at University of New England, **Mr. Naoto Goto** at New York Islanders Hockey Club, and **Mr. Jason A. Pachter** and **Mr. Kevin J. Joyce** at Plattsburgh State University of New York, for their encouragement.

In addition, I would like to acknowledge a part of this project (Chapter 6) has been funded from **National Strength and Conditioning Association Graduate Research Grant 2006**.

Finally, I wish to thank my parents **Emiko and Seiichi Hori**, my grand parents **Kiyoko and Tatsuki Okamura**, **Kiyono and Muneshige Hori**, and my brother **Masafumi Hori** for all of their support.

DEDICATION

This thesis is dedicated to
athletes and coaches who devote their life to
Olympic Gold Medals.

PUBLICATIONS FROM THE THESIS

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M., R., Kraemer, W. J., & Nosaka, K. (In Review). Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *Journal of Strength and Conditioning Research*

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M., R., Andrews, W. A., Chapman, D. W., & Nosaka, K. (In Press). Comparison of weighted jump squat training with and without eccentric braking. *Journal of Strength and Conditioning Research*

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M., R., & Nosaka, K. (In Press). Does performance of hang power clean differentiate performance of jumping, sprinting and changing of direction? *Journal of Strength and Conditioning Research*

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M., R., & Nosaka, K. Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *Journal of Strength and Conditioning Research, 21*(2), 314-340

Hori, N., Newton, R. U., Nosaka, K., & McGuigan, M. R. (2006). Comparison of different methods of determining power output in weightlifting exercises. *Strength and Conditioning Journal*, *28*(2), 34-40

Kawamori, N., **Hori, N.**, Andrews, W. A., Nosaka, K., & Newton, R. U. (2006). Relationships between change of direction performance and measures of strength and power. *J. Strength Cond. Res.*, *20*(4), e3

Hori, N., Newton, R. U., Nosaka, K., and Stone, M. H. (2005). Weightlifting exercises enhance athletic performance that requires high-load speed strength. *Strength and Conditioning Journal*, *27*(4), 50-55

Hori, N., Newton, R. U., Nosaka, K., & McGuigan, M. R. (2005). Comparison of system versus barbell force, velocity and power in hang snatch. *Journal of Strength and Conditioning Research*, *19*(4), e19

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND NOMENCLATURE

ANOVA	Analysis of variance
BG	Braking Group
BW	Body weight
CH	Concentric hamstring strength
cm	Centimeter, the unit of distance
CMJ	Countermovement jump
COD	Change of direction
COG	Centre of gravity
CQ	Concentric quadriceps strength
CV	Coefficient of variation
DJ	Drop jump
°	Degree, the unit of angle
°/s	Degree per second, the unit of angular velocity
EH	Eccentric hamstring strength
EMG	Electromyography
EQ	Eccentric quadriceps strength
FT	Fast twitch
GRF	Ground reaction force
HPC	Hang power clean
Hz	Hertz, the unit of frequency
ICC	Intra-crass coefficient of correlation
IH	Isometric hamstring strength
IQ	Isometric quadriceps strength
J&R	Jump and reach
kg	Kilogram, the unit of mass
m	Meter, the unit of distance
mm	Millimeter, the unit of distance
m/s	Meter per second, the unit of velocity

ms	Millisecond, the unit of time
N	Newton, the unit of force
NBG	Non-Braking Group
Nm	Newton-meter, the unit of torque
Ns	Newton-second, the unit of impulse
RFD	Rate of force development
RM	Repetition maximum
RPD	Rate of power development
RSI	Reactive strength index
s	Second, the unit of time
S.D.	Standard deviation
SJ	Squat jump
Sq Con	Half squat concentric only
Sq Ecc-Con	Half squat from eccentric to concentric
SSC	Stretch-shortening cycle
ST	Slow twitch
W	Watt, the unit of power
WJS	Weighted jump squat
yr	Year, the unit of age

CHAPTER 1

INTRODUCTION

Power is the mechanical quantity defined as the rate of doing work, and is determined by work divided by time or force times velocity (Newton & Kraemer, 1994). For many sporting movements, success of performance is largely dependent on how much power is applied toward objects (e.g. ground, ball, or sporting equipment) (Newton & Kraemer, 1994). Thus, improving power output during the vast array of movements that must be produced in sports is one of the most important goals for strength and conditioning programs (Baker, 2001a). Previous studies (Baker, 2002; Barker et al., 1993; Fry & Kraemer, 1991; Young et al., 2005) have reported that athletes with high playing ability (playing at higher level, or selected as a starter) also possess higher capability of power output than athletes with low playing ability (playing at lower level, or not selected as a starter) in rugby league, Australian Rules football and American football. Also, there are significant correlations between the power output measured during a vertical jump movement and sprint time among rugby league players (Baker & Nance, 1999a; Cronin & Hansen, 2005).

To enhance power output during a given resistance-training exercise, it is recommended that an object (i.e. a barbell and/or an athlete's body) be projected into the air so that the undesirable deceleration is minimized (Newton et al., 1996). In this thesis, such conditions will be described as "ballistic". Newton et al. (1996) compared the biomechanical characteristics between ballistic bench throws and traditional bench press. They reported power increased toward the end of range of motion during bench throw, but power decreased over the last 40% of the range of motion during bench press due to the eccentric muscle action of antagonist muscle groups. Unless the object (the barbell in this case) is released from the hands and projected into the air, the kinetic energy generated during the early phase of the range of motion needs to be absorbed by musculoskeletal structures (Newton et al., 1996). However, once the barbell is projected into the air, its kinetic energy is safely controlled by the gravitational force, so that it allows athletes to keep applying power with maximum effort through the entire range of motion (Newton et al., 1996).

For this reason, the weighted jump squat has been proposed as a more suitable form of resistance training exercise to enhance power output compared to squat or leg press (Newton & Kraemer, 1994; Newton et al., 1999; Wilson et al., 1993). This exercise has attracted considerable attention among scientists and practitioners as a method of increasing power because of the significant and meaningful improvements that have been reported (McBride et al., 2002; McEvoy & Newton, 1998; Newton et al., 1999; Wilson et al., 1993). In addition, weightlifting exercises (i.e. snatch, clean and jerk, and variation of these exercises) have similar characteristics to the weighted jump squat. In the pulling movement of weightlifting exercises, the athletes extend their hip, knee, and ankle joints as rapidly as possible, and their force production is significantly correlated with that of vertical jumping (Canavan et al., 1996; Garhammer & Gregor, 1992). As a result, weightlifting exercises have been utilized as a method to improve power among athletes competing in a range of sports (Ebben & Blackard, 2001; Ebben et al., 2004; Simenz et al., 2005).

To maximize athlete performance at the most important competitions, practitioners usually plan and implement their training program with long term strategies based on the theory of periodisation (Fleck, 2002; Plisk & Stone, 2003). For example, the focus of training may shift from maximum force output, maximum power output, and finally power output during a specific sports task. Before and after each training mesocycle (e.g. every 4-8 weeks), it is important to assess the athletes power output capability, so that practitioners can monitor the adaptations that are induced as a result of the given training program and possibly detect overtraining (Baker, 2001a; Newton & Dugan, 2002). Thus, how scientists and practitioners can validly and reliably measure power output during resistance exercises is a critical question. In recent studies, it is common to measure power output during weighted jump squat and weightlifting exercises by using one of the following methods; (1) using a position transducer, velocity and force are calculated from displacement-time data using inverse dynamic approach (Stone et al., 2003a); (2) using a force platform, velocity is calculated from force-time data using the forward dynamic approach (Kawamori et al., 2005); (3) using a force platform synchronized with a position transducer, force data obtained from the force platform is multiplied by the velocity data obtained from the position transducer (Young et al., 2005). If kinematic data is obtained from a position transducer tracking the barbell, it assumes that the displacement of the barbell is representing the displacement of the centre of gravity (COG) of the system (i.e. a barbell and a lifter) (Dugan et al., 2004). If this assumption does not hold, then it will result in an error in the subsequent calculation of power. Theoretically, the power output values obtained from a force platform would only be the most logical and valid methodology. However, the validity of the other methods has not been adequately investigated to date.

There is clearly a need for future investigations to examine the validity of methodologies. Another aspect which scientists and practitioners need to consider is the sampling frequency of the testing equipment (e.g. force platform). In general, the force platform using higher sampling frequencies is more expensive. Also, the sampling frequency of a portable force platform is lower than that of the force platform permanently mounted in the laboratory. Hence, it is important for the scientists and practitioners to consider what would be the minimum required sampling frequency for measuring power output during resistance exercises. For example, commonly cited studies (Haff et al., 1997; Harman et al., 1990; Harman et al., 1991; Sayers et al., 1999) sampled GRF-time data at 500 Hz. However, not many previous studies have reported the power output values calculated from force-time data sampled lower than 500 Hz. Thus, there is a need to examine the reliability and validity of the power output and other measures obtained from various sampling frequencies to determine minimum recommended rates.

While measuring power output directly during resistance exercises is the most appropriate way to evaluate an athlete’s capability of power, not all practitioners have access to testing equipment for such measurements. Therefore, it would be useful to establish an alternative testing method that can be administrated easily in a practical setting. Weightlifting exercises have similar biomechanical characteristics to the weighted jump squat, and these exercises are widely utilized as a method of developing athletes’ capability of power. Therefore, if the performance of the weightlifting exercises represents the athletic performance (e.g. sprint speed, jump height), practitioners may consider weightlifting exercises as a valid measurement of athletes’ neuromuscular performance. Previous studies (Fry & Kraemer, 1991; Fry et al., 1991) reported the athletes with high playing ability in American football and volleyball possess higher performance in one repetition maximum (1RM) power clean. Thus, it would be of interest to practitioners whether the athletes who have high performance in weightlifting exercises actually have high performance in common sports tasks such as jumping, sprinting and changing of direction.

While the efficacy of the ballistic exercises (e.g. weighted jump squat, weightlifting exercises) are already proven, scientists and practitioners need to be aware of their safety aspects. Once the athletes' body and the barbell are projected and leave the ground, they are accelerated downward due to the influence of gravity. In weightlifting exercises, the vertical displacement of the COG is much smaller than in jump movements (Garhammer, 1993), so that weightlifting exercises have much less landing impact compared to the weighted jump squat (Chiu & Schilling, 2005). However, in the weighted jump squat, the athletes are exposed to considerable magnitude of landing impact at the initial foot contact (Humphries et al., 1995). For example, Humphries et al. (1995) reported the peak GRF during the propulsive phase in weighted jump squat was 2.19 times body weight (BW), but the peak GRF during the landing phase was 3.04 BW. If athletes are exposed to such high impact force repetitively, it may cause overuse injuries such as cartilage degeneration, stress fractures, and tendonitis (Humphries et al., 1995; Ricard & Veatch, 1990).

To minimize such high impact forces at landing, previous training studies (McBride et al., 2002; McEvoy & Newton, 1998; Newton et al., 1999; Wilson et al., 1993) have utilized electromagnetic braking mechanisms. With this mechanism, upward force is applied while the barbell moves downward, reducing acceleration and thus the impact force at the landing phase can be effectively reduced during weighted jump squats (Humphries et al., 1995). However, in attempting to reduce the impact force at the landing, this mechanism can also alter the natural use of the stretch-shortening cycle (SSC) prior to the propulsive phase. Previous literature (Bobbert et al., 1996; Moore & Schilling, 2005; Walshe et al., 1998) has suggested that the eccentric phase of countermovement jump (CMJ) allows the jumper to exert higher force at the beginning of subsequent concentric phase, and higher net impulse is achieved over the concentric muscle action. Thus, reducing the eccentric load prior to the concentric phase might be limiting the stimulation as well as adaptation of the weighted jump squat training. Hence, if athletes can tolerate the impact force at landing phase, weighted jump squat training without the braking mechanism might be more effective to develop power than training with the braking mechanism. Hoffman et al. (2005) has compared the effects of weighted jump squat training on strength, power and athletic performance in collegiate American football players. They reported that the weighted jump squat training without braking mechanism was more effective for improving 1RM power clean and squat. However, since their subjects were competitive athletes, there were several limitations in this study. For example, all subjects had to participate in their normal strength training and conditioning program in addition to the training intervention. This limitation could have made it difficult to detect the differences between the specific adaptations to these two conditions. Therefore, further investigation under more controlled conditions would provide better understanding of this research question.

Research Questions

The purpose of this series of studies was to examine the following research questions.

- Study 1
    - What is the validity and reliability of power output and related performance measurements during a common testing and training exercise such as CMJ?
    - What is the influence of reducing sampling frequencies on validity and reliability of power output and related measurements during the CMJ?

- Study 2
    - Is there any difference between the power output values obtained from the different methods commonly used to measure performance such as force platform only, position transducer only, and force platform synchronized with position transducer?
    - What are the relationships between values obtained from these different methods?

- Study 3
    - Do athletes who have high performance in hang power clean have high performance in sprinting, jumping and change of direction (COD)?

    - What are the relationships between the performance of hang power clean and measurements of strength, power and athletic performance?

- Study 4
    - What are the differential effects of weighted jump squat training, with and without a braking mechanism to modify the eccentric load, in terms of strength, power and athletic performance over an 8-week training intervention?

Significance of the Thesis

Strength and conditioning is rapidly developing as a field of scientific endeavor and standardization of measurement techniques is important in this maturation. Valid and reliable methodology to measure power output is especially critical for scientists and practitioners working with highly trained athletes because their windows of adaptation are very small and only modest though very important adaptations may be realized from various phases of a periodised training program. In many instances, it is a fine line between best enhancement of performance and overtraining and injury when attempting to optimize training quality and quantity. As such, it is important to be able to accurately quantify training loads as well as detect and monitor the athlete's progress. Measurement of power output through a range of methods is imperative given that this neuromuscular performance characteristic appears so indicative of athlete preparedness for training and competition.

Further, understanding the specific adaptation in two different conditions of weighted jump squat training is very important. Since weighted jump squat training is such a popular resistance training exercise among athletes, they experience numerous sets and repetitions of these exercises through their career. If scientists and practitioners understand the differential effects of the two conditions of weighted jump squat training, athletes can avoid undesirable risk of injuries and induce desirable adaptations.

CHAPTER 2

REVIEW OF LITERATURE

1. Introduction

During a given sporting task completed in a very short period of time, the success is largely dependent on the athlete's power output capacity. Thus, scientists and practitioners spend considerable effort to understand how power should be assessed and developed and much research has been directed to this topic over the last two decades. In competitive athletes, power must be developed through a long term strategy based on the theory of periodization (Fleck, 2002; Plisk & Stone, 2003). To implement such programs, the athlete's power output capacity needs to be periodically assessed, and practitioners and scientists must make appropriate adjustment in their strength and conditioning programs accordingly. This literature review firstly discusses the rationale of why power is so important, neural and intramuscular mechanisms underlying maximal power production, and then the methodological aspects of measurement of power output during common resistance training exercises follows. Finally, a comprehensive strategy of the selection of exercises and loads to develop the ability to exert high power during a given sport task is examined.

2. Relationship between Power and Athletic Performance

In many sport tasks completed within a few repetitions of maximum effort, such as jumping and sprinting, success of performance is largely dependent on the ability to exert large amount of force over a short period, particularly with high velocity (Schmidtbleicher, 1992). For example, jumping performance (for maximum height) is predominantly determined by the velocity of COG at the moment of take off. When force is applied toward the floor over hip and knee extension as well as ankle planter flexion, it causes changes in momentum, and this determines velocity at take off. Once the athlete has left the floor, the athlete is no longer able to apply force against the floor, and the faster the acceleration during the upward movement, the shorter the duration the athlete can apply force (Newton & Kraemer, 1994). Therefore, the ability to output high work over a short time during a given task is essential for many athletic performances.

The capacity of work done within a unit of time is often assessed by measuring power output during ballistic resistance exercises completed in short duration such as vertical jump (Baker, 2001a; Newton & Dugan, 2002). It is essential that any test for the capability of power output closely mimics the biomechanical characteristics of the sport task for which the athlete is training (Newton & Dugan, 2002). In the sports requiring tasks that involve the lower extremities, athletes who have higher playing ability seem to have higher power capacity during jumping (Baker, 2002; Barker et al., 1993; Fry & Kraemer, 1991; Young et al., 2005). Baker (2002) reported professional rugby league players exhibited significantly higher power output than high school players during weighted jump squat with 20 kg weight, and Young et al. (2005) reported starters exhibited higher power output than non-starters during weighted jump squat with 40 kg weight and CMJ without external load in professional Australian Rules football players.

Although the performance in competition is dependent on many factors especially in team sports, there is agreement among previous studies (Barker et al., 1993; Fry et al., 1991; Hoffman, 1996; Young et al., 2005) that starters usually have higher performance than non-starters in jumping, sprinting, and COD except for one study (Hoffman et al., 2003). It is well documented that power output during vertical jump movement is correlated with sprint performance (Baker & Nance, 1999a; Cronin & Hansen, 2005; Young et al., 2005). For example, Baker and Nance (1999a) reported there was significant correlation ($r = 0.52-0.76$) between sprint performance measured by 10 and 40 m distance and power measured during weighted jump squat with several different loads. Importantly, the power output values were divided by the athletes' body mass in this study. When data were analyzed by using absolute power output values, there were no significant correlations (0.02-0.17). Therefore, the capability of power output relative to body mass, rather than the absolute value, should be of interest among scientists and practitioners. In addition to the cross sectional studies mentioned above, several longitudinal studies (McBride et al., 2002; Newton et al., 1999; Wilson et al., 1993) examining the effects of various training interventions have reported that the improvements of jump or sprint performance are associated with improvement of power output measured during the vertical jump movement.

Despite the significant relationships between power output during vertical jump and sprint time, the relationships between power and COD remains unclear (Young & Farrow, 2006). For example, Young et al. (Young et al., 2002) has examined the relationships between several different measurements of strength (torque output during modified squat movement with two legs and one leg only) and performance of a variety of COD tasks (e.g. changing to different directions, different number of turns, and different angles of turn). They reported that the strength of correlation was varied (r = 0.04-0.54) depending on the patterns of COD tasks. Another study (Young et al., 2001b) also suggested that improvement in COD performance is highly specific to which kind of training has been done, particularly for its skill aspects (i.e. which kind of running pattern has been practiced).

Although the relationship between power and COD performance is not definitive, it seems reasonable to consider the power output during vertical jump movement as a valid measurement of athletic performance. In addition to jumping movements, weightlifting exercises are often utilized among practitioners both as a method of testing and training (Chiu & Schilling, 2005; Haff & Potteiger, 2001; Stone, 1993). Weightlifting exercises are the exercises used for training and competition in the sport of weightlifting (i.e. snatch and clean and jerk) and their variations (e.g. hang power snatch and hang power clean). Since weightlifting exercises have similar biomechanical characteristics to jump movements (Canavan et al., 1996; Garhammer & Gregor, 1992), it is possible that weightlifting exercises could be applied as a useful method of testing for athletes' neuromuscular performance (further explanation in Section 5.2).

3. Neuromuscular Adaptation to Resistance Training

Resistance training is performing exercises that require the body to move (or attempt to move) against an opposing force created by resistance, and it has been considered as an effective way to develop power among athletes (Fleck & Kraemer, 2004b). Resistance can be applied through barbells, medicine balls, elastic bands, or even one's body weight. As a result of resistance training, the neuromuscular system adapts to the imposed stress, and such adaptations are observed from several different aspects. In this section, basic mechanisms of physiological adaptation of the neuromuscular system to resistance training are introduced. However, it should be noted a complete review of this topic is beyond the scope of this thesis but rather a synopsis is provided to set the theoretical framework for the experimental chapters and in particular the training intervention.

3.1. Cross Sectional Area, Pennation Angle, and Fascicle Length

An individual's capability of maximum power output is largely dependent on muscle cross sectional area because the concentration of actin and myosin per cross sectional area is constant. Thus, hypertrophy is one of the factors to contribute to the improvement of strength and power (Schmidtbleicher, 1992). In a study by Kawakami et al. (1995), five men participated in a 16-week resistance training program, and parallel increases of muscle layer thickness and strength were reported.

However, the improvement of strength is not always accompanied by hypertrophy. In the first few weeks of training in untrained individuals, the improvement of strength is predominantly due to neural factors (explanation provided in Section 3.3) rather than hypertrophy (Moritani & deVries, 1979). Also, even after years of high level of training experience, degree of hypertrophy is dependent on the given program regimes. A study by Häkkinen et al. (1985) reported hypertrophy was noted during a lower intensity training phase, but not in a higher intensity training phase of their 24 week of training intervention. In another study by Häkkinenn et al. (1988), strength and power improved over two years of training, but changes in muscle fiber size were minimal in competitive weightlifters.

If individual reaches certain level of hypertrophy, increase of pennation angles in pennate muscle can be observed (Kawakami et al., 1995). Kawakami et al. (1995) reported that pennation angle of the triceps brachii increased as a result of resistance training. Because the direction of the force applied to tendon moves away from the longitudinal axis of the tendon, increased angle of pennation is unfavorable to rapid force production, thus possibly limiting power production (Newton & Kraemer, 1994). In reality, however, it is very unlikely that typical strength and power training causes such excessive hypertrophy in athletes in most of sports. To induce large hypertrophy in trained athletes, high volume of training (e.g. 6-14 sets of 10 repetition maximum) is required which takes hours of training, and most of athletes can not afford that much time due to their training for skill and other strength qualities (Newton & Kraemer, 1994).

Another aspect of muscle architectural adaptation is changes in fascicle length. Increase in fascicle length is noted as a result of:

- Increase in pennation angle reaches a stage of plateau (Kearns et al., 2000);
- Combination of weight training, sprint and jump training (Blazevich et al., 2003);
- Sprint and jump training alone (Blazevich et al., 2003).

Increase in fascicle length is associated with increase in number of sarcomeres in series (Kearns et al., 2000), and it is considered as advantageous to develop high power output because longer fibers contract at faster velocity than shorter fibers (Sacks & Roy, 1982). For example, Kumagai et al. (2000) reported that a group of faster sprinters have longer fascicle lengths and smaller pennation angles than another group of slower sprinters. Changes in fascicle length and pennation angle can be observed in as little as 5 weeks, and factors inducing such changes seems to be the force and velocity characteristics of the activity, rather than movement similarity (Blazevich et al., 2003).

Recently, Blazevich et al. (2003) has reported the changes in pennation angle and fascicle length as a result of a 5-week sprint and jump training intervention. In this study, three groups undertook one of the following training regimes; 1) combination of typical weight training, sprint and jump, 2) combination of weight training specifically mimic sprinting, sprint and jump, and 3) sprint and jump only. The two groups that undertook weight training showed increase of pennation angles in their vastus lateralis, but the group that undertook sprint and jump training only showed decrease of pennation angle in the same muscle. This study also reported the increase in fascicle length as a result of training intervention. Fascicle length was calculated from muscle thickness and pennation angles at distal and proximal sites of vastus lateralis and rectus femoris muscles. Increases of fascicle length were noted in the groups who undertook a combination of typical weight training, sprint and jump training as well as the group that undertook sprint and jump training only.

3.2. Fibre Type

Human skeletal muscle is classified based on its characteristics of the speed and shape of the muscle twitch with stimulation, fast-twitch (FT) or slow-twitch (ST) fibres (Fleck & Kraemer, 2004b). Alternatively, muscle fibres are also divided into type I or II by using muscle biopsy and myosin ATPase staining method or myosin heavy chain analysis (Fleck & Kraemer, 2004b). FT or Type II fibres can generate larger force more rapidly than ST or Type I fibres, but FT or Type II fibers have a greater fatigue rate than ST or Type I fibers (Fleck & Kraemer, 2004b). Thus, FT or Type II fibers are suitable to perform high intensity, short duration task. Type I and Type II have several distinct sub-types, such as type I, IC, IIC, IIAC, IIA, IIAB and IIB (Fleck & Kraemer, 2004b). Type IC is a less aerobic form than type I, type IIC is the most oxidative fiber in type II, type IIA has good aerobic and anaerobic characteristic, type IIB has good anaerobic characteristic and poor aerobic characteristic, and type IIAB has a characteristic between type IIA and IIB (Fleck & Kraemer, 2004b).

Fry et al. (2003b) and Fry et al. (2003a) reported significant difference in percent of fibre types and area between trained and untrained subjects. For example, a group of powerlifters exhibited significantly higher percentage of type IIA and lower percentage of type IIB fibres, but there was no significant difference between percentages of type I fibres compared to the untrained subjects (Fry et al., 2003b). In another example, a group of weightlifters again exhibited significantly higher percentage of type IIA and IIC and significantly lower percentage of type IIB fibres compared to the untrained subjects, but there was no difference between percentages of type I, IC, or IIAB fibres (Fry et al., 2003a).

It has been proposed that fiber type is transferable dependent on the given physiological stimulus and functional demands, such as Type I ↔ IC ↔ IIC ↔ IIAC ↔ IIA ↔ IIAB ↔ IIB (Pette & Vrbova, 1992). Although it is questionable if typical resistance training induces any transformation from Type IC to Type IIC (Fleck & Kraemer, 2004b), transformation from Type IIB → IIAB → IIA due to the resistance training has been reported in as little as 2 weeks among untrained individuals (Staron et al., 1994). In a study by Staron et al. (1994), men and women participated into two sessions of weight training for 8 weeks, and they improved their strength without any changes in muscle mass. Importantly, the improvement of strength was accompanied with significant decrease of type IIB fibers.

It was reported that trained individuals have higher percentage of type IIA and lower percentage of type IIB fibers (Fry et al., 2003a; Fry et al., 2003b), and strength improved with decrement of this type of fiber (Staron et al., 1994). Therefore, it is reasonable to consider transformation of fiber type from type IIB to type IIA as a positive adaptation to resistance training. However, changes in fiber types might be dependent on the given training intervention and subjects' resistance training background. Changes in fiber type may be one of the possible mechanisms of improvement of power, but other factors such as neural adaptation may take a more important role (McGuigan et al., 2003).

3.3. Neural Factors

Electromyography (EMG) is the recording and analysis of the electrical activity of neural innervation at the muscle and is used commonly for the research into neural changes with training (Behm, 1995; Moritani, 1992). The EMG signal contains characteristics representative of; 1) recruitment of motor units, 2) their firing frequency, and 3) synchronization of these impulses (Behm, 1995). Häkkinen et al. (1985) reported the increase of maximal force was accompanied by significant increases in maximum integrated EMG during the high intensity phase of their training intervention. This study also reported rate of EMG onset was significantly correlated with rate of force development, an important strength quality for maximal power output (Newton & Kraemer, 1994). Further, fiber area, lean body mass and girth measurements did not indicate any significant hypertrophy during this training phase. This suggests that neural factors form an important role in strength improvement.

Typically, type I fibres are recruited first in a muscle action to achieve the given task (overcome the resistance), and type II fibres are followed as more force is required than type I fibres alone can generate in a continuum from the slowest to fastest characteristics (Fleck & Kraemer, 2004c). As described in Section 3.2, type II fibres have higher ability to generate large force rapidly, but type I fibres have higher fatigue tolerance. Therefore, such order of recruiting different types of muscle fibres, called "size principle", is efficient to avoid fatigue in type II fibres (Fleck & Kraemer, 2004c). Type II fibres have a higher threshold to recruit, thus this type of fibre are recruited only when the exercises are characterized by near maximum effort (i.e. high force, power, and/or velocity), and the ability of neuromuscular system to recruit high threshold muscle fibres is one of the known neural adaptations to resistance training (Fleck & Kraemer, 2004c).

Muscle fibres are activated by electronic impulses generated in the brain and transmitted by the motor nerves to the muscle fibres. The frequency of this train of impulses is another factor to determine the recruitment of muscle fibres. Force can be increased by recruiting larger numbers of motor units, as well as increasing the firing rate of motor units (rate coding) (Behm, 1995; Fleck & Kraemer, 2004c). While all motor units need to be recruited to exert maximal force during a given task, it is required that the firing rate of the recruitment also to be high enough. However, untrained individuals may not be able to recruit such high threshold fibres voluntarily. Therefore, developing the ability to recruit all motor units during a given task is considered one of the important parts of the training adaptation (Fleck & Kraemer, 2004c) combined with activation at a high enough frequency.

In addition to the ability of each muscle group to exert high force, it is also important that all muscle groups work efficiently to complete the given task in well coordinated manner. The success in a given task is determined by interaction between agonist, antagonist and synergists involved in the joint movement. For example, there must be complementary relaxation of antagonist muscle groups (ranging from 10-80%) while agonist muscle groups exert high force (Fry & Newton, 2002). Thus, even if athletes develop the power output during a given resistance training exercise, whether such recruitment pattern is directly transferred to another task or not is dependent on whether the athlete possesses the ability to coordinate their movement. Thus, practitioners need to take account of the "lag time" to allow athletes to learn how to utilize the strength developed in the weight room for subsequent transfer to performance in sports (Young, 2006). For example, Bobbert and Van Soest (1994) reported a simulation study that examined the effect of strength improvement on vertical jump performance. In this study, the improvement of strength alone without the appropriate adjustment of control of timing has detrimental effects on jump height. In other words, the development of strength will enhance athletic performance only if appropriate skills are practiced and optimization of coordination are accompanied.

Another possible neural adaptation is control of inhibitory mechanisms of Golgi tendon organs (Fleck & Kraemer, 2004c). Golgi tendon organs are the proprioceptors located within the tendons, and monitor the tension developed by muscle. When muscles are exposed to a threshold level or higher tension, Golgi tendon organs inhibit the activation of agonist muscle groups to protect muscles from injuries. This phenomenon is often found in untrained individuals, particularly during high force/low velocity tasks (Caiozzo et al., 1981; Wickiewicz et al., 1984). This inhibition mechanism can be a factor to limit muscular force development, but it has been suggested resistance training may cause voluntary inhibition of these protective mechanisms, and the ability to control this protective function is considered one of the neural adaptations to strength and power training (Fleck & Kraemer, 2004c).

4. Methods of Measuring Human Power Output

Position transducers (e.g. linear position transducer, video camera, infrared/ultrasound technique) and force platforms are widely utilized by scientists and practitioners. By using this equipment, the power output during resistance training exercises can be determined, and measuring power output gives scientists and practitioners useful information to evaluate an athlete's progress (Newton & Dugan, 2002).

Since weightlifting exercises are effective training methods, and cause less landing impact than jump squats, many athletes utilize these exercises in their training (Chiu & Schilling, 2005). Thus, it would be helpful if they could measure the power output in weightlifting exercises and in particular understand the limitations of the different measurement systems. Further, while many studies have measured power output in the weighted jump squat using a position transducer and/or a force platform (Baker, 2001a; Baker & Nance, 1999b; Chiu et al., 2003; Dugan et al., 2004; McBride et al., 1999, 2002; Newton et al., 1999; Wilson et al., 1993), only few studies have been done on weightlifting exercises to date (Cormie et al., 2007a; Cormie et al., 2007b; Haff et al., 1997; Haff et al., 2003; Kawamori et al., 2005; Moore et al., 2003; Winchester et al., 2005). While there are four common methods to obtain power output in weighted jump squat (Dugan et al., 2004), it is important to know if it is appropriate to utilize all of these four methods for measuring power output in weightlifting exercises.

The purpose of this section is to discuss the various methods commonly used to measure power output in weighted jump squat and weightlifting exercises. In the following sections, the four common methods to measure power output in weighted jump squat will be introduced. This will be followed by discussion of whether these methods can be applied to measure power output in weightlifting exercises. Finally, there will be an examination of how practitioners can utilize the power output data for testing and training their athletes.

4.1. Measuring Power Output in Weighted Jump Squat

Ground reaction force (GRF) can be determined by performing weighted jump squats on a force platform, and barbell displacement data can be obtained by using a position transducer attached to a bar. Usually, data is collected as analogue signal from a position transducer and force platform, then converted to digital data and interfaced with computer hardware. Once data are stored in computer hardware, calculations are performed by dedicated software. By using either or both GRF and barbell displacement data, there are four possible methods of obtaining power output in the jump squat (Dugan et al., 2004).

- Method 1: Calculation from barbell displacement and known mass (barbell mass and lifter’s body mass)
- Method 2: Calculation from barbell displacement and known mass (barbell mass only)
- Method 3: Calculation from GRF and known mass (barbell mass and lifter’s body mass)
- Method 4: Calculation from barbell displacement and GRF

In Method 1, the displacement data is obtained at each time point based on the sampling rate (number of measurements of position recorded per second). Velocity is calculated from displacement data and sampling rate using the process of differentiation which basically involves determining the rate of change of displacement between successive samples (Winter, 1992). To calculate acceleration data, the process is repeated, termed “double differentiation”, but in this case the rate of change of velocity between two consecutive time points is calculated (Winter, 1992; Wood, 1982). Force is then calculated by multiplying the known mass (barbell mass and lifter’s body mass) by the acceleration data, and power is calculated by multiplying the force data by the velocity data (Dugan et al., 2004). This method assumes the displacement of COG of the system mass (total of barbell mass and lifter's body mass) is the same as the displacement of the barbell (Dugan et al., 2004). This is clearly a limitation of the method as even a cursory observation of the weighted jump squat movement reveals that the lifter's body and in particular the lower legs and feet do not move synchronously with the barbell. This technique which estimates force output based on the displacement-time data is called *inverse dynamics approach* (Hamill & Selbie, 2004). While Methods 3 and 4 directly measure GRF, displacement-time curve is differentiated twice in Method 1. As a result, any noise in the row signal can be amplified (Wood, 1982), thus the GRF value obtained from this method is not as accurate as Methods 3 and 4.

In Method 2, the process of calculation is similar to Method 1. The only difference is that the lifter's body mass is not included in the calculation of force and subsequently power output. This does overcome the problem of assuming the barbell movement is representative of the whole system of barbell and lifter (Chiu et al., 2004). However, one should note that the power output value obtained from Method 2 will be significantly lower than Methods 1, 3 and 4 because only the power being applied to the barbell is being calculated and as such this method underestimates the actual power output of the leg and trunk extensors being applied to the ground (Dugan et al., 2004). This method has the added advantage that it can be utilized for measuring power output in a wide range of resistance exercises including upper body movements such as the bench press.

In Method 3, the force exerted by the feet on the ground is directly obtained from a force platform at each time point. From force data, acceleration is calculated by dividing the force by the known mass (barbell mass and lifter's body mass) since force is the product of mass and acceleration (Dugan et al., 2004). Velocity is calculated from the force data using the impulse-momentum relationship (equation 1).

Equation 1: $F \bullet t = m\left(v_f - v_i\right)$

Where F = force, t = time, m = mass, vf = final velocity, vi = initial velocity

This process which predicts movement of the system from force-time data is termed *forward dynamics approach* (Hamill & Selbie, 2004). This technique involves integration (calculation of area under the curve) of the force-time data and dividing by the known mass to determine change in velocity between consecutive samples (Dugan et al., 2004). A crucial requirement for this analysis is that the initial velocity at the start of data collection must be zero. In other words, when data collection starts the lifter and barbell must be stationary. Power output is calculated by multiplying the measured force by the calculated velocity (Dugan et al., 2004). Since force is obtained from the force platform as GRF, it does not matter if the COG of the barbell and that of the lifter move simultaneously or separately, and the lifter's body mass is included into the calculations of velocity and power. This method is also prone to errors in velocity and power calculation as the integration process magnifies any slight measurement errors in force. For this reason, it is critical that the force plate system is accurately calibrated and in particular is correctly zeroed prior to data collection (Dugan et al., 2004). A further limitation is that the system must be isolated on the force platform and no part of the lifter or barbell can be in contact with any other surface. For example, the lifts can be started from anywhere in mid-thigh, knee, or below knee level, but it is not possible to validly measure power output by using Method 3 during the exercises started from the floor (e.g. power snatch from floor). While the barbell is in contact with the floor, the weight (mass times gravity) of the barbell is not applied to the force platform. Then, as soon as the barbell is lifted off, the weight of the barbell is applied to the force platform through the lifter's feet in addition to the weight of the lifter's body. In this manner, the system weight force applied toward the force platform is not accurately incorporated to the calculation of the velocity (Caldwell et al., 2004).

In Method 4, force is obtained directly from a force platform, and velocity is obtained from barbell displacement data. Thus, power is obtained as the product of the force and velocity data. As in Method 3, the lifter's body mass and barbell mass is included in the calculations since the force data is directly obtained from force platform as GRF. In this method, data are sampled from the force platform and position transducer simultaneously. Since force data includes the lifter's body mass and velocity data are based on the barbell displacement, there is the limitation already discussed of assuming the COG of barbell and that of lifter are moving as one (Dugan et al., 2004). The advantage of this method is that displacement is measured directly and a much better approximation of barbell velocity is obtained. Also, measurement of force developed through the feet is direct and more accurate than the value obtained from a position transducer as explained Methods 1 and 2. As long as the COGs of barbell and body move simultaneously, there is less risk of errors occurring compared to the other methods (Dugan et al., 2004). However, the applicability of this method is limited to lifts in which the bar moves with the lifter, as when the bar is held on the shoulders in the jump squat. It is not applicable for lifts like the jerk, in which the body and bar move at different velocities and even in different directions.

In Methods 1, 2, and 4, if displacement-time data is obtained from a linear position transducer, the movement need to be linear since this equipment can track one direction of kinematic data only (Chiu et al., 2004). Although the purpose of weighted jump squats and weightlifting exercises is to move the bar upward, it has been documented that there is bar horizontal movement during these lifts (Garhammer, 1993; Stone et al., 1998). Thus, it is a significant limitation of linear position transducers. The advantage of a linear position transducer is this instrument allows sampling displacement data with much higher frequency compare to using video camera or infrared/ultrasound technique (e.g. V-scope, Lipman Electronic Engineering Ltd., Ramat Hahayal, Israel). For example, Cormie et al. (2007a) used linear position transducers, Stone et al. (2003a) and Rossi et al. (2007) used the infrared/ultrasound technique, and Winchester et al. (2005) used a digital video camera, and the sampling frequecies in those studies were 1,000, 66, 50 and 60 Hz respectively. To take advantage of its high sampling frequency and to overcome the aforementioned limitation, Cormie et al. (2007a) has suggested to synchronize two linear position transducers, so that barbell vertical and horizontal displacement can be traced at high sampling frequency.

It has been suggested that data collected over time should be sampled at least twice the signal of interest, which is known as the Nyquist criterion (Derrick, 2004). However, in reality, it is recommended sampling frequency to be at least 5-10 times of the frequency of the signal of interest (Derrick, 2004). As a result, it seems like at least 100 Hz are necessary in typical human movement such as jump if inverse dynamics approach is performed (Garhammer, 1993). However, studies (Haff et al., 1997; Harman et al., 1990; Harman et al., 1991; Sayers et al., 1999) commonly cited in this area had reported the data sampled at least 500 Hz when forward dynamic approach is performed. Apparently, sampling frequency reported in these studies (Garhammer, 1993; Haff et al., 1997; Harman et al., 1990; Harman et al., 1991; Sayers et al., 1999) were far higher than Nyquist criterion.

No matter which method is utilized, power can be obtained at any time point, so that it can be reported as the peak power, or average between two time points (e.g. mean power during the propulsive phase). Among previously reported research, McBride et al. (1999), McBride et al. (2002) and Newton et al. (1999) reported peak power, Baker and Nance (1999b) and Wilson et al. (1993) reported mean power, and Chiu et al. (2003) reported both peak and mean power in the weighted jump squat. Theoretically, both mean and peak values will provide a good representation of athlete's performance. However, in terms of absolute explosiveness of the movement, the peak value might be more relevant (Dugan et al., 2004). Harman et al. (1990) reported that peak power had a higher correlation to vertical jump performance than mean power ($r = 0.88$ vs. $r = 0.54$). This is because the high power is exhibited within a very short time (e.g. the last 150 ms of the jump), and mean power was affected by total time taken (i.e. total time can be lengthened or shortened by slowing down or speeding up parts of the movement) (Harman et al., 1990).

4.2. Measuring Power Output in Weightlifting Exercises

In weightlifting exercises such as the snatch and clean, the COG of the barbell and that of the lifter's body move independently. For example, in the second pull phase of snatch, the COG of the lifter's body moves only 0.12 to 0.15 m while COG of the barbell moves from lifter's thigh to overhead a distance of up to 0.8 m (Garhammer, 1993).

Since Methods 2 and 3 are valid even if the COG of a barbell and that of a lifter move separately, these methods are preferred to measure power output in weightlifting exercises. Theoretically, if the interest of coaches is to evaluate the lifting performance, it seems that Method 2 gives more important information because the success of weightlifting depends on the power applied to the barbell and thus how high the lifter can pull (in the snatch and clean) or drive (in the jerk) the barbell rather than the lifter's body. On the other hand, if the athlete's leg and trunk extensor power output capability is of primary interest, Method 3 would best express this. If the athlete's power output capability is the issue, it is better to include the lifter's body mass into the calculation because weightlifting exercises involve considerable amount of movement of the lifter's body mass (Garhammer, 1993).

As previously stated, Method 1 and 4 are valid only if the COG of a barbell and that of a lifter’s body move simultaneously, but the COG of a barbell and that of a lifter’s body move independently during weightlifting exercises. Thus, Method 1 and 4 are not logical for measuring power output during weightlifting exercises. In general, a position transducer is less expensive than a force platform. Roughly, the cost of a position transducer can be $1,000 or less while the cost of a force platform is usually at least $15,000. Thus, if data using Methods 2 and 3 are well correlated, practitioners may consider a position transducer to be adequate equipment even if their interest is the athletes’ power output capabilities rather than their lifting performance. However, currently there is a only one study (Cormie et al., 2007a) comparing the values obtained from different methods of determining the power outputs in weightlifting exercises, and all other studies used one method only. For example, Moore et al. (2003) and Haff et al. (2003) measured power output by using Method 2 only, Kawamori et al. (2005) and Haff et al. (1997) used Method 3 only, and Winchester et al. (2005) used Method 4 only. Cormie et al. (2007a) reported significant difference between the values obtained from these different methods during the power clean from floor. However, Method 3 is valid only if the system is isolated on the force platform as mentioned earlier (see Section 3.1.). Thus, the power output values obtained from the force platform by Cormie et al. (2007a) could be incorrect since the power clean was started from floor. To examine the validity of these different methods, future research needs to measure power output during the other weightlifting exercises such as hang power clean, which is not started from floor.

4.3. Practical Application

If scientists and practitioners measure the power output in weightlifting exercises or jump squats using several different external loads, the power output can be different at each external load. The effects of different external loads on power output are explained by the fact that the power is the product of force and velocity, and the higher the external load, the lower the velocity output and the higher the force output (Baker, 2001a).

The highest power output value among the measurements at several different loads is called the maximum power output (Baker, 2001a; Newton & Dugan, 2002). Potentially, maximum power output is one of the most important mechanical quantities to determine athletes’ performance in strength/power oriented sports (Newton &

Kraemer, 1994). Therefore, monitoring the maximum power output may give scientists and practitioners useful information. Baker (2001a) has closely monitored the maximum power output of his athlete, and found the maximum power output clearly reflects the conditioning of the athlete. He reported the maximum power output correspondingly increased if the athlete positively adapted to the strength training program, and decreased if the athlete had stopped training due to intense competition. For example, the maximum power output increased from 1,426W to 1,811W as a result of 12 weeks of strength/power training, and then decreased to 1,661W after the competition and following active recovery.

The load at which the maximum power output is achieved is called the optimal load (Baker, 2001a; Newton & Dugan, 2002). Kaneko (1983) et al. reported 30% of isometric maximum force as the optimal load, and suggested athletes train with loads of 30% of isometric maximum force. However, the optimal load appears to be different from exercise to exercise, as well as from individual to individual (Cormie et al., 2007b; Kawamori et al., 2005; Kawamori & Haff, 2004). In addition, the optimal load will increase after the maximum strength phase, and decrease after the maximum speed phase, so that the optimal load can be different in each test occasion even within the same individual (Baker, 2001a; Newton & Dugan, 2002). Because of this individual difference, Kawamori et al. (2005) reported no statistical difference between the peak power outputs of 15 male subjects performing hang power clean with 50, 60, 70, 80, and 90% of 1RM loads. Thus, if practitioners need to know the optimal load for each athlete, it is necessary to periodically administer the power output measurements using several different weights with narrow range (i.e. every 5-10kg, or every 5-10% of 1RM). By monitoring the optimal load, practitioners can see how the athletes have adapted to the previous training periods as described above (Newton & Dugan, 2002).

However, measuring power output for every 5 kg (i.e. 40, 45, 50, 55, 60, 65, 70, and 75 kg) takes a considerable amount of time. Spending too much time could be a problem for those who coach many athletes and have limited time available for testing (e.g. coaches for football, ice hockey, baseball). If that is the case, it may not be practical to measure power output using a number of different loads. It may be more efficient to measure power output at one or two loads only (e.g., 40 kg and 60 kg). As a result of chronic training, the power output at the same external load should increase (Winchester et al., 2005). Therefore, as long as the same loads are used in every test, coaches can monitor the improvement of athletes' power output even if they can see neither the athletes' maximum power output nor the optimal load. In addition, if power output decreases at the same loads, it may be because of fatigue, and this could be useful measure to prevent overtraining.

In summary, scientists and practitioners can use either a force platform or a position transducer to measure power output in resistance training exercises. However, they should be aware of the limitations and assumptions of each method. In the calculation of power in weightlifting exercises, only barbell mass should be used when a position transducer is used. On the other hand, when a force platform is used, both barbell mass and lifter's body mass should be used. Both methods are logical and valid, and by using one or both of these methods, scientists and practitioners can monitor the athletes' power output capability at any external load. However, further investigation of the validity of these methods is needed. If power outputs are measured at several different external loads, maximum power output and optimal load can be obtained. By observing these values, scientists and practitioners can monitor how athletes respond to long term training programs.

5. Strength Qualities Determining Power

The power output during a given task is determined by a number of factors such as gravitational acceleration, friction between athletes' shoe and floor surface, and most importantly, how the athletes apply force toward the objects (e.g. floor, ball, and/or sporting equipment). The ability to exert force is termed "strength" (Knuttgen & Kraemer, 1987). The force athletes can exert is dependent on the task, such as the duration and velocity of muscle contraction (Schmidtbleicher, 1992). Thus, strength needs to be assessed and developed from multifaceted aspects (Newton & Dugan, 2002; Newton & Kraemer, 1994). If the training exercises emphasizing several different strength qualities are combined in a well balanced manner, such a combination is more effective to enhance power and athletic performance than the training emphasizing a single strength quality alone (Adams et al., 1992; Harris et al., 2000). In this section, strength qualities that scientists and practitioners need to take account of are reviewed.

5.1. Power Applied to Light and Heavy Loads

Newton and Kraemer (1994) state power is determined by multifaceted strength qualities rather than any single aspect of strength, particularly 1) the ability to develop high force rapidly, and 2) the ability to continue producing high force during high velocity, are paramount to maximize power. These strength qualities can be termed “rate of force development” and “speed strength” (Newton & Dugan, 2002). Force and velocity characteristics as a factor to determine power over a certain period (e.g. concentric phase of vertical jump) can be analyzed as discussed in Section 4. The masses that must be manipulated during a given task in sports range from a part of the body (e.g. arms in throwing, legs in kicking, or whole body in jumping) to opposition bodies (tackling in football). Thus, it is important to remember that having high capacity in one task does not necessarily mean that this will transfer to other tasks due to the specificity of the neuromuscular system. With this in mind, Newton and Dugan (2002) recommended scientists and practitioners measure power output across light to heavy loads during a given task (e.g. weighted jump squats with light and heavy loads). For example, sprinters can produce higher power than powerlifters during weighted jump squats with light loads, but powerlifters can produce higher power than sprinters with heavy loads (McBride et al., 1999). Most likely, it is because of the difference in their training background. In a landmark study by Kaneko et al. (1983), 20 men were divided into four different training groups, and undertook the training programs using a custom made bicep curl machine for 12 weeks. The training loads were 100, 60, 30, and 0% of isometric maximum force in respective groups. The group that trained with 100% load improved their performance in the high force and low velocity task, and the group that trained with 0% load improved their performance in the low force and high velocity task, while the group that trained with the 30% load exhibited the best overall improvement. These studies (Kaneko et al., 1983; McBride et al., 1999) suggest that power output in different tasks might be a result of different strength qualities and that adaptation of the strength quality to the given training intervention is highly specific.

5.2. Maximum Strength

Literature (Baker & Nance, 1999b; Moss et al., 1997; Newton & Dugan, 2002; Newton & Kraemer, 1994; Stone et al., 2002; Stone et al., 2003a; Stone et al., 2003b) suggests that maximum strength is one of the important factors for determining power output even during the task performed against sub maximal load. Maximum strength is the ability to exert one’s highest force during a given condition (i.e. isometric or dynamic) without the restriction of time (Newton & Dugan, 2002). If an individual possesses higher maximum strength, then a given resistance would represent a smaller percentage of his/her capability of maximum force, thus the given mass would be accelerated more easily (Stone et al., 2003a). In addition, the individual who possesses higher maximum strength would also have higher percentage of type II fibres which is advantageous for exerting higher power. It is because alteration in fibre type (specific hypertrophy in type II fibres, or increase in the ratio between type II/I cross sectional area) may occur as a result of training for maximum strength (Stone et al., 2003a).

In cross sectional studies (Baker & Nance, 1999b; Stone et al., 2003a), maximum strength measured by 1RM or 3RM back squat was significantly correlated with the power output during the weighted jump squat with light loads. Also, long term observational studies reported changes in maximum strength measured by 1RM bench press was significantly correlated to power output during bench throw over 19 weeks (Baker, 2001b) and four years (Baker & Newton, 2006) among college-aged and professional rugby league players respectively. Furthermore, if training with an emphasis on high power is combined with training with emphasis on maximum strength, the maximum power capability has been more effectively improved compared to one training regime alone (Adams et al., 1992; Harris et al., 2000).

5.3. Stretch-Shortening Cycle

Another important strength quality to consider is the ability to utilize SSC. SSC is the phenomenon that more powerful concentric action is achieved following a rapid eccentric and subsequent brief period of isometric actions than without such rapid eccentric action (Fleck & Kraemer, 2004a). SSC is a natural characteristic of many human movements, and is observed during numerous occasions in sports and daily activity such as walking, running, and jumping. SSC can be further divided into two distinct phenomena; long SSC (e.g. block jump in volleyball) and short SSC (e.g. taking off in high jump). Long SSC has a ground contact time more than 250 ms, and short SSC has a ground contact time less than 250 ms (Schmidtbleicher, 1992). In long SSC, therefore, larger angular displacements are observed in the involved joints compared to those in short SSC (Fleck & Kraemer, 2004a). It has been noted that athletes can exert higher power output or achieve higher jump height during CMJ than squat jump (SJ) that is a form of vertical jump for which the concentric action is initiated after a few seconds of pause thus without SSC (Bobbert et al., 1996; Stone et al., 2003a).

The complete mechanisms of how the preceding eccentric action enhances the performance in subsequent concentric action in SSC are somewhat contentious. The following factors have been proposed in previous literature but the relative contribution of each continues to attract considerable debate (Bobbert et al., 1996; Fleck & Kraemer, 2004a; Komi, 2003; Walshe et al., 1998).

- While SSC is a natural movement, not many individuals are familiar with movements without using SSC (Bobbert et al., 1996). This can be one of the possible explanations as to why performance in SSC condition is higher than that in a non-SSC condition (e.g. jump height achieved in CMJ vs. SJ).
- In the SSC condition, higher force is exerted at the beginning of the concentric phase than that in the non-SSC condition (Bobbert et al., 1996). As explained Section 4.1., change in momentum during concentric phase of movement is a result of net impulse. Thus, if higher force is exerted at the beginning of concentric phase, and such high force is to be maintained through the range of motion, it must create larger impulse and therefore change in velocity. In the non-SSC condition, it takes time before the muscle develops its maximum force due to the following reasons (Bobbert et al., 1996):
    - The finite rate of increase of muscle stimulation by the central nervous system (stimulation dynamics);
    - The time constants of the stimulation-active state coupling (excitation dynamics);
    - The interaction between contractile elements and series elastic elements (contraction dynamics).

  Walshe (1998) reported that this delay in non-SSC condition can be avoided if muscle reaches a maximally activated state prior to the beginning of concentric action by execution of the eccentric phase of SSC condition, or even isometric pre-load.
- In SSC conditions, elastic energy is stored during eccentric phase, and utilized or recovered in the subsequent concentric phase (Bobbert et al., 1996; Fleck & Kraemer, 2004a; Komi, 2003).
- Muscle stretch occurring in SSC condition triggers spinal reflex and longer-latency responses (Bobbert et al., 1996; Fleck & Kraemer, 2004a) facilitating muscle contraction.

- In SSC condition, the pre-stretch of active muscle alters the property of the contractile machinery, and it causes enhancement of force production (Bobbert et al., 1996). This enhancement is called “potentiation” (Cavagna, 1977).
- In SSC condition, there seems to be an interaction between the contractile mechanics and the tendonous recoil of the musculo-tendonous unit (Komi, 2003). Due to the high stretch load in SSC condition, tendonous extension is greater relative to that of muscle (Komi, 2003). Hence, the muscle fibers may stay at the same length or even shorten while the whole musculo-tendonous unit is lengthening. In this mechanism, rapid recoil of the tendonous structure allows muscles to be operated at close to the optimal length and velocity (Walshe et al., 1998).

At least during CMJ, the fact that the higher force is exerted at the beginning of concentric phase is the most important mechanism to explain why jump height in CMJ is higher than that in SJ (Bobbert et al., 1996). In fact, Newton (1997) stated the ability to utilize SSC is partially dependent on maximum strength. This is because there must be a brief moment that muscle exerts the maximum force in isometric action at the changeover from later phase of eccentric action to early phase of concentric action. If athletes can tolerate higher force developed during later part of the eccentric phase, the early phase of concentric action starts with higher force output, thus higher impulse would be achieved (Newton, 1997). However, the relative contribution of each mechanism may differ from task to task (Fleck & Kraemer, 2004a; Komi, 2003). Therefore, further studies are still required in this topic, especially during activities that have different biomechanical characteristics from CMJ.

5.4. Strength Diagnosis

Newton and Kraemer (1994) have proposed that an efficient method for improving power is to identify the athlete’s least developed strength quality, and then specifically target it for training emphasis. To evaluate the athlete’s strength qualities appropriately, it is important to assess each strength quality specifically and the test result should be reflected in the training program. This process is called strength diagnosis (Newton & Dugan, 2002). The definition of each strength quality varies throughout the literature (Newton & Dugan, 2002; Newton & Kraemer, 1994; Young, 1995b). Examples of commonly referenced classification systems for strength include:

- Newton and Dugan (2002): Maximum strength, high load speed strength, low load speed strength, rate of force development, reactive strength, skill performance and power endurance;
- Young (1995b): Maximum strength, speed strength, and strength endurance;
- Newton and Kraemer (1994): Slow velocity strength, high velocity strength, rate of force development, stretch shortening cycle, and intermuscular coordination and skill.

Although the classifications and definitions of strength qualities vary, there is a consensus that the athletes' neuromuscular performance cannot be explained by any single measurement. Thus, previous studies investigating athletes' strength qualities have utilized some combination of different testing measurements ranging from light load/high velocity tasks to heavy load/low velocity tasks (McBride et al., 2002; Newton et al., 1999; Young et al., 2005). In addition, several studies suggest assessing how efficiently the athletes utilize short SSC using drop jump (Newton & Dugan, 2002; Young, 1995a), and long SSC using the ratio between CMJ and SJ (McGuigan et al., 2006) since those strength qualities can be a factor for determining the power output during a certain sport task. The drop jump is a test (as well as a form of training, see Section 6.1) in which the athlete drops off a box (e.g. 40 cm height), and then jumps as high as possible with minimum foot contact time immediately after the landing (Newton & Dugan, 2002). The performance of drop jumps is assessed by either flight time divided by contact time or jump height divided by contact time (Newton & Dugan, 2002; Young, 1995a). Examples of typical testing batteries to assess strength qualities are:

- 3RM leg press, power output during weighted jump squat with 40 kg, CMJ, SJ, and peak torque during isokinetic knee extension and flexion (60°/s) (Young et al., 2005);
- 1RM squat, power output during weighted jump squat with 30, 55, and 80% of 1RM load (McBride et al., 2002);
- 1RM squat, power output during weighted jump squat with 30, 60 and 90% of 1RM load, CMJ and SJ, flight time divided by contact time during drop jump (Newton et al., 1999).

Once the athlete's individual strengths and weaknesses are determined, their training should address specific deficiencies which may be limiting their power development (Newton & Dugan, 2002). For example, one may need to train with high force against heavy resistance during slow movements (e.g. squat with near maximum load), but others may need to train with high power against range of heavy to light loads (e.g. weighted jump squat, jump without external load). However, unless the athlete has particular weakness, it is generally accepted that long term planning starts from the development of maximum strength, and is then followed by the emphasis in high power output (Fleck, 2002; Plisk & Stone, 2003).

6. Exercises Which Exhibit High Power Output

To improve the ability to produce high power output, it is important that the athletes intend to accelerate the object (e.g. the barbell or the athlete's body itself) through the entire range of motion, and the object is not decelerated using the eccentric action of antagonist muscle groups (Newton et al., 1996). Examples of these movements are jumping and throwing, and such exercises are called "ballistic exercises". The word "ballistic" refers to the fact that the object is released at the completion of movement and projected into the air as in a throw or a jump (Newton & Kraemer, 1994). Newton et al. (1996) compared the kinetics and kinematics of the barbell during bench throw and bench press performed explosively in a Smith machine. In the bench throw, the bar was projected from the lifters' hands and actually thrown, and then the bar velocity and power increased toward the end of range of motion. However, in the bench press, bar velocity and power was decreased toward over the last 40% of the movement. In the bench press, even if athletes try to keep accelerating their movements, they must decelerate the bar velocity at the end of range of motion. This is because the kinetic energy they created in early concentric phase must be absorbed by musculoskeletal structures unless the weight is released from their hands (Newton et al., 1996). In this manner, the power output cannot be improved efficiently.

6.1. Plyometric Exercises

Plyometrics are a form of resistance exercise that emphasizes SSC such as jumping, hopping, bounding or throwing (Fleck & Kraemer, 2004a). In addition to the utilization of SSC (see Section 5.3), its ballistic nature (e.g. jumping) is very suitable to exert high power through the entire range of motion without the activation of antagonist muscle groups (Newton & Kraemer, 1994). Typically, plyometric exercise is performed using the athletes' own body weight or relatively light external load (e.g. medicine ball). A comprehensive review (Markovic, 2007) has reported plyometric training is effective to enhance jumping performance. For example, previous studies have reported that drop jump training significantly improved CMJ performance (Lyttle et al., 1996; Wilson et al., 1993). However, although jumping with body weight is effective for developing the ability to apply high power toward light load (low-load speed strength), this form of exercise does not effectively develop the ability to exert high power toward heavy loads (high-load speed strength). In general, high-load speed strength is not developed enough through traditional weight training, sports skill training, or plyometric exercises, so that the athletes need to perform exercises specifically to develop such a strength quality (Newton et al., 1999; Wilson et al., 1993). As a result, a considerable numbers of studies (McEvoy & Newton, 1998; Newton et al., 1999; Wilson et al., 1993) support the efficacy of plyometric exercise with relatively heavy external loads (e.g. weighed jump squat).

6.2. Weighted Jump Squat

6.2.1. Effects of Weighted Jump Squat on Power and Athletic Performance

Wilson et al. (1993) compared the effects of 10 weeks of three different training methods; 1) traditional squat, 2) drop jump and 3) weighted jump squat. Their test measurements included 30m sprint, 6 seconds cycling, counter movement jump (CMJ), squat jump (SJ), isokinetic knee extension and isometric squat. In this study, the weighted jump squat group exhibited the largest improvements from pre- to post-training. Since then, practitioners have widely utilized weighted jump squat as a part of their strength and conditioning programs (Baker, 2007; Baker & Nance, 1999b).

After Wilson et al (1993) suggested the efficacy of the weighted jump squat training, a remaining question was "Is weighted jump squat really better than the combination of traditional weight training and jump training (e.g. plyometric exercise, volleyball game and practice)?". Lyttle et al. (1996) compared the effects of an 8-week training of weighted jump squat/bench throw versus combination of traditional weight training and plyometric exercise (drop jump/medicine ball throw). They reported that both training groups improved their strength and power capacities from pre- to post-training intervention, but there was no difference between groups. They concluded that weighted jump squat/bench throw training and a combination of traditional weight training and plyometric exercise were equally effective. However, this result needs to be interpreted with caution. The subjects in this study had not been involved in any specific weight training or plyometric training prior to the training intervention. With untrained populations, any training stimuli may induce significant effects, so that it is difficult to detect inherent adaptations to different training modes.

Newton et al. (1999) compared the effects of eight weeks of two different training methods, traditional squat/leg press, and weighted jump squat, on jump performance of highly competitive volleyball players. Their test measurements included a variety of jumps, and the weighted jump squat group produced superior improvements. In this study, one team of highly competitive and well trained volleyball players with extensive resistance training background were divided into two groups, so that both training groups participated into the same amount of skill training for volleyball. Opposed to the study by Lyttle et al. (1996), Newton et al. (1999) clearly demonstrated the efficacy of the weighted jump squat training among highly developed athletes with extensive resistance training history. Interestingly, neither group produced any improvement of 1RM squat in this study. The window for improvement of maximum strength could be very limited in these subjects since they had extensive training history (Newton et al., 1999).

The training load used by Wilson et al. (1993) and Lyttle et al. (1996) was about 30% of isometric peak force, and the load used by Newton et al. (1999) et al. was two sets each of 30, 60 and 80% of 1RM squat. Since Wilson et al. (1993) and Lyttle et al. (1996) used one load only, and Newton et al. (1999) used a range of different loads, another research question had arisen; was there any specific adaptation to the weighted jump squat training using different load? More recently, McBride et al. (2002) and McGuigan et al. (2003) investigated the differential effects of the weighted jump squat training using 30% versus 80% of 1RM half squat loads. For the training, subjects were asked to move the barbell as rapidly as possible no matter which load was used, so that the velocity of movement was determined by load (i.e. weighted jump squat with 30% load is faster than that with 80% load) (McBride et al., 2002; McGuigan et al., 2003). McBride et al. (2002) reported both groups improved their power output during the weighted jump squat with 30, 55 and 80% loads. However, the group trained with 30% load improved their sprint performance while the group trained with 80% load actually sprinted significantly slower than pre-training. This study also measured average EMG during the weighted jump squat with 30, 55 and 80% load before and after the training intervention. The group trained with 30% improved average EMG across all loads, but the group trained with 80% load improved this measurement in 55 and 80% load only. As a result, they (McBride et al., 2002) suggested adaptation of neural activation of the muscle as well as athletic performance to the prescribed weighted jump squat training is specific to the load (thus velocity), so that the adaptation to the training with heavy load might not necessarily transfer to the performance with high velocity.

Although McBride et al. (2002) reported significant changes in strength, power and athletic performance after the training intervention, McGuigan et al. (2003) did not find any changes in fibre type using this training. If a training program was designed with high training volume accompanied by short rest periods between sets, the shifts in fiber type distribution from IIB to IIA should be observed. McGuigan et al. (2003) stated that typical weighted jump squat training emphasizing power output is a much smaller volume compare to the typical hypertrophy emphasized training, and this could account for the lack of muscular changes. McGuigan (2003) also stated that the changes in strength, power and athletic performance accompanied to weighted jump squat training is predominantly due to neural adaptation, rather than changes in muscle structure. Since the adaptations to the training stimulus are so specific, practitioners need to consider the optimal combination of different types of training regimes based on a long term strategy (see Section 7).

6.2.2. Landing Phase during Weighted Jump Squat

During weighted jump squats, the athletes usually place a barbell on their shoulders, lower themselves to their comfortable depth (typically about 90° of knee flexion), and then jump to maximum vertical height (propulsive phase). After this, the athlete's body and weight fall under the influence of gravity until they contact the ground again and initiate the landing phase. During the landing phase, athletes are exposed to considerable GRF particularly the impact spike of initial contact (Humphries et al., 1995). For example, Humphries et al. (1995) reported the peak impact force at landing was 3.04 times body weight (BW) while the peak force during the propulsive phase was 2.19 BW during the weighted jump squat with only a 10 kg load.

The GRF experienced by the athlete can be divided to two categories; passive and active force (Nigg, 1985; Nigg et al., 1981). In passive force, peak is observed within the initial 50 ms following contact. Whereas, peak appears after the initial 50 ms in active force (Nigg, 1985; Nigg et al., 1981). This classification is based on the fact that the reaction time of the neuromuscular system is 50-75 ms (Nigg, 1985; Nigg et al., 1981). It is difficult for the athlete to absorb passive force since passive force is too rapid to react, so one concern is that the passive force in landing may cause injury to the athlete such as cartilage degeneration, stress fractures, and tendinitis (Humphries et al., 1995; Ricard & Veatch, 1990). To minimize the passive force during landing phase, previous studies (Lyttle et al., 1996; McBride et al., 2002; McEvoy & Newton, 1998; McGuigan et al., 2003; Newton et al., 1999; Wilson et al., 1993) have used braking mechanisms and reduced passive force effectively. For example, Humphries et al. (1995) reported that an electromagnetic braking system reduced the peak force at landing by 155% and the impulse for the first 50 ms of landing phase by 200%. In their study (Humphries et al., 1995), the braking mechanism was activated only as the barbell descended, and the barbell's upward movement during the propulsive phase was not affected at all. However, if the eccentric phase is modified, a natural stretch shortening cycle (see Section 5.3) is not experienced. This may reduce the training stimulus, and thus the amount of neuromuscular adaptation. Therefore, for practitioners to embrace this form of training, they must know whether the weighted jump squat with eccentric braking is as effective as the weighted jump squat without eccentric braking to improve athletes' strength, power and athletic performance.

The magnitude of passive force during the landing phase varies depending on the load, jump height, landing technique, shoe type, muscle fatigue, postural variation, and previous medical history (James & Bates, 2003). Devita (1990) reported that athletes can decrease the magnitude of passive force by using hip and knee flexion during landing. Interestingly, even if the athletes can not react to the passive force, experienced athletes can anticipate that they will be exposed to the passive force, so that they prepare to bend their hips and knees while they are in the air (Devita & Skelly, 1990). During the landing phase of the weighted jump squat, muscle groups of the lower extremity work eccentrically (Hoffman et al., 2005). It has been well documented that unaccustomed eccentric muscle actions cause greater muscle damage than concentric muscle actions (Dierking & Bemben, 1998; Szymanski, 2001). Hoffman et al. (2005) mentioned eccentric muscle action during the landing phase of the weighted jump squat causes additional muscle damage.

However, the magnitude of muscle damage is significantly reduced once trainees become accustomed to the training activities (Nosaka & Clarkson, 1995). In addition, several studies (Brandenburg & Docherty, 2002; Hortobagyi et al., 2001; Kaminski et al., 1998) have reported that training consisting of eccentric actions improves strength more than that of concentric actions. Moreover, other studies (Bobbert et al., 1996; Doan et al., 2002; Moore & Schilling, 2005; Walshe et al., 1998) reported eccentric action during the descending phase enhances subsequent concentric action during ascending phase in jump, squat or bench press movements. Furthermore, Baker (2007) and Baker and Nance (1999b) suggested there should be a minimal risk of injuries due to this form of exercise as long as the application of overload is gradual and progressive. Thus, once the trainees become accustomed to the exercise, the landing phase of the weighted jump squat may improve the athletes' strength and eventually power and athletic performance without causing severe muscle damage. If this eccentric muscle action initiates a positive adaptation, it is possible that weighted jump squats without eccentric braking system may be more beneficial than that with reduction of eccentric load.

The study by Hoffman et al. (2005) is the only study which has compared the effects of weighted jump squat training with and without eccentric braking on strength, power and athletic performance. They reported that the weighted jump squat without the eccentric braking was more effective than with reduced eccentric load to improve 1RM power clean and squat among competitive collegiate American football players. However, further investigation is needed to confirm the effect of the eccentric muscle action during landing phase, since the finding of Hoffman et al. (2005) may not necessarily be applicable for other conditions (i.e. training equipment: machine vs. free weight, training load, or subjects' training history). Another limitation was that both groups in this study (Hoffman et al., 2005) had to participate in their normal strength and conditioning program, thus this might mask the differential effects of weighted jump squat training.

6.3. Weightlifting Exercises

6.3.1. Characteristics of Weightlifting Exercises

While the efficacy of the ballistic exercises such as weighted jump squat has been widely recognized, weightlifting exercises seem as popular as, or even more popular to emphasize high power output (Baker, 2007; Newton & Kraemer, 1994).

During the pull phase of clean and snatch as well as the drive phase of jerk, athletes extend their hip, knee and ankle joints to push against the ground as hard and as rapidly as possible at a given weight (Garhammer & Gregor, 1992). As a result, the lifters' feet are often projected into the air, and re-positioned for receiving (Schilling et al., 2002). Once the system, which means barbell and lifter in the weightlifting exercise, is projected into the air, the kinetic energy is decelerated by the influence of gravity, not by the undesirable eccentric action of antagonist muscle groups (Newton et al., 1996). The "ballistic" nature of weightlifting exercises are considered very similar to the weighted jump squat which allows lifters to maximize bar velocity without the deceleration due to eccentric action of antagonist muscle group (Newton & Kraemer, 1994). As soon as their feet are back on the floor, agonist (not antagonist) muscle group works eccentrically similarly to weighted jump squat (see Section 6.2.2.) (Chiu & Schilling, 2005). Although the mechanism of absorbing impact force is essentially the same in weightlifting exercises and weighted jump squat, displacement of COG of the lifter him/herself is only 0.09-0.18 m in weightlifting exercises (Garhammer, 1993), which is much smaller than that during weighted jump squats. Thus, it seems like the impact force at receiving phase in weightlifting exercises are much smaller than that in landing phase of jump movement (Chiu & Schilling, 2005).

6.3.2. Evidence to Support That Weightlifting Exercises Improve Athletic Performance

Several studies have investigated the relationship between weightlifting exercises and jump performance (Canavan et al., 1996; Carlock et al., 2004; Garhammer & Gregor, 1992; Hoffman et al., 2004; Stone et al., 1980; Stone et al., 2003b). Canavan et al. (1996) compared the movements of hang power snatch from above the knee and non-counter movement (concentric only) vertical jump in collegiate athletes who were familiar with these exercises. They reported similarities in maximal power, time to maximal power, relative power, maximal force, and time to maximal force between the hang power snatch and vertical jump movements. Garhammer and Gregor (1992) showed that GRF in the snatch was similar to that of counter movement vertical jump. Such biomechanical similarities between snatch and vertical jump explain the findings from Stone et al. (1980) and Carlock et al. (2004). Stone et al. (1980) reported that weightlifting exercises training improved vertical jump height, and 1RM snatch and clean significantly. Carlock et al. (2004) also showed a strong correlation between weightlifting performance and jump performance in weightlifters. From these studies

(Canavan et al., 1996; Carlock et al., 2004; Garhammer & Gregor, 1992; Stone et al., 1980), it seems that weightlifting exercises are effective for improving jump performance. However, further research involving long term training interventions are required.

Few studies (Hoffman et al., 2004; Stone et al., 1980; Stone et al., 2003b; Tricoli et al., 2005) have addressed the effects of weightlifting exercises on sprinting, stopping, changing direction, and throwing to date. Stone et al. (2003b) reported a strong correlation between isometric clean pull and throwing performance (shot put and weight throw). However, there is a paucity of studies investigating effects of weightlifting training in comparison to other types of resistance training on athletic performance, particularly other than vertical jump movement. Hoffman et al. (2004) compared the effects of weightlifting versus powerlifting training using twenty college football players. One group participated in a program consisting of weightlifting exercises mainly, and another group participated in a program consisting of powerlifting (squat, bench press, and deadlift) exercises predominantly. They found that the weightlifting group improved jump performance significantly more than the powerlifting group. However, there was no significant difference between groups for improvement of sprint and agility performance. This may be due to the fact that all subjects participated in sprint form drills, agility drills, and conditioning sessions in addition to weightlifting or powerlifting exercises during the last five weeks of the training. In addition, the training program for both groups included the squat, so it is difficult to differentiate the two groups clearly. Tricoli et al. (2005) have reported that the improvement in jumping and sprinting performance was larger for a weightlifting group compared with a vertical jump training group after an 8-week training intervention performed three times a week. However, the study used physical education students as subjects who had no lower-body strength training for three months prior to the investigation. Therefore, it is questionable if the findings from this study can be applied to athletes, particularly those who already have an extensive resistance training background. Further investigation is warranted involving well controlled training interventions to address some of the weaknesses of previous training studies (Hoffman et al., 2004; Tricoli et al., 2005).

Although further studies are warranted to reveal the exact relationships between weightlifting exercises and other sports tasks, weightlifting exercises are incorporated as a part of training and testing for many programs around the world (Ebben & Blackard, 2001; Ebben et al., 2004; Simenz et al., 2005). Thus, it would be of interest among practitioners whether the performance of weightlifting exercises (1RM) can be a valid test measurement to represent athletes' neuromuscular performance. Previously, Fry et al. (1991) reported that the athletes with higher playing ability in collegiate American football (Division I) had higher 1RM power clean than the athletes with lower playing ability (Division III). Fry et al. (1991) also reported that the starters had higher 1RM power clean than non-starters in collegiate volleyball. More recently, Baker and Nance (1999a) reported significant correlations between 3RM hang power clean and sprint time among a professional rugby league team. However, to consider the 1RM of weightlifting exercise as a valid test for athletes' neuromuscular performance, the future study needs to examine whether athletes who have higher performance in weightlifting exercises also has higher athletic performance.

7. Selection of Training Load to Develop Power

It appears important that practitioners understand there is an optimal combination of load and volume (i.e. repetitions and sets) to be lifted in each training session based on a long term strategy (Kawamori & Haff, 2004). As described previously (see Section 4.3.), power is the product of force times velocity, thus there is an optimal combination of force and velocity in which power is maximized. Kaneko et al. (1983) found the power to be maximum if the load is 30% of isometric maximum force during testing in a custom built bicep curl machine. This study also reported the capability of power output was most effectively developed when subjects trained using the load that produced maximum power output. Their finding was supported by Wilson et al.(1993) that compared the training effects of three different exercises (see Section 6.2.2.). Since these findings (Kaneko et al., 1983; Wilson et al., 1993), scientist and practitioners have investigated what load is the best to maximize power output during the common resistance training exercises such as weighted jump squat, bench throw, and weightlifting exercises (Baker et al., 2001a, 2001b; Cormie et al., 2007b; Dugan et al., 2004; Kawamori et al., 2005; Kawamori & Haff, 2004). There is a wide range of differences between studies on the optimal load to maximize power output due to exercise investigated, training level of subjects, methodology to measure power, and methodology to describe loads (e.g. % of isometric peak torque, % of 1RM). For example, the optimal load in weighted jump squats has ranged from 0% to 55-59% (Baker et al., 2001b; Cormie et al., 2007b; Stone et al., 2003a), and optimal load in power cleans has ranged from 70% to 80% (Cormie et al., 2007b; Kawamori et al., 2005).

Although the efficacy of training with optimal load has been proven (Kaneko et al., 1983; Wilson et al., 1993), practitioners have to consider whether this finding is applicable to actual strength and conditioning programs for competitive athletes. Most training studies (Kaneko et al., 1983; Newton et al., 1999; Wilson et al., 1993) have investigated the effects of a training intervention for only two to three months, but the majority of competitive athletes have been training for a much longer time (i.e. from the beginning of off-season to the end of competitive season, typically a year). It is widely accepted that the training program should be designed based on a long term strategy (Fleck, 2002; Plisk & Stone, 2003). Thus, yearly training plans should consist of several different phases emphasizing different strength qualities. In general, the underpinning strength qualities to determine the capability of power (e.g. maximum strength) need to be developed prior to the phase emphasizing power. Whereas, the training effect would be minimal or it would cause overtraining if athletes keep training using optimal load all the time (Kawamori & Haff, 2004).

Furthermore, since the adaptation of power output capability in highly trained athletes seems to be specific to the velocity which the athletes use in their training, it is important to consider the training load as being specific to the task in the sports (Kawamori & Newton, 2006). Previous studies (Behm & Sale, 1993; Moss et al., 1997) have suggested that the capability of force/power during fast movements would improve by training at slow movement or even isometric training as long as the trainee's intent was to move the object rapidly. However, Kawamori and Newton (2006) pointed out that these studies had used untrained populations as their subjects. Alternatively, McBride et al. (2002) reported that the weighted jump squat training with 30% of 1RM load was much more effective in enhancing sprint performance than the training with 80% load. This study suggested that training with lighter loads was more specific to sprinting, thus training with light load transferred better than training with heavy loads. In other words, the improved power output capability at heavy external loads may not necessarily transfer directly to the task involving the movement of body weight only, especially if the athletes have an existing background of resistance training (Kawamori & Haff, 2004; Kawamori & Newton, 2006; Young, 2006). Therefore, especially in well trained athletes, practitioners need to consider what loads athletes encounter during their sports (Cormie et al., 2007b; Kawamori & Haff, 2004). For example, the load that rugby players need to overcome during tackling (i.e. the body mass of opponent) can be used for specific preparation (e.g. weightlifting exercises, weighted jump squat with heavy load), and the load that they need to overcome during the sprinting (i.e. own body mass) can be used for specific preparation for sprinting (e.g. jump without external loads).

Thus, from the available literature, practitioners need to determine the load to be used from several different perspectives.

- In early phase of the long term plan (e.g. several months prior to the season), focus should be development of the underpinning strength qualities determining power in later training phases (see Section 5). In the meantime, some ballistic exercises can be introduced with light loads.
- As the competition gets closer (e.g. 4-8 weeks prior to the season), the load that maximizes the capability of maximum power output would be utilized. (Kaneko et al., 1983; Wilson et al., 1993).
- A few weeks before the season, the load that the athletes encounter during the specific sport task would allow athletes to most effectively enhance athletic performance (Kawamori & Haff, 2004; Kawamori & Newton, 2006).

8. Summary and Implications from the Literature Review

Assessment and development of an athlete’s capacity for power output during their sporting tasks have been an important research topic among scientists and practitioners (Newton & Dugan, 2002; Newton & Kraemer, 1994). Because of the specificity of muscle groups involved, types of muscle actions, range of motion, and pattern of movements, the power output during the vertical jump is often considered to represent the power potential during many athletic performances as it indicates underlying leg extensor qualities (Newton et al., 2002). Thus, the reliability and validity of mechanical quantities (i.e. power, velocity and force over time) during the vertical jump movement need to be thoroughly examined. Further, the influence of the frequencies at which data are sampled has received little attention, and further study is required in this area.

Currently several different methodologies to measure power output are available, but the characteristics of each methodology have not been comprehensively investigated (Cormie et al., 2007a; Dugan et al., 2004). Since different studies utilized different methodologies to measure power output, such inconsistency makes their results difficult to compare to the other studies (Cronin & Sleivert, 2005). Therefore, it is very important to investigate the characteristics of each method and relationships between the values obtained from different methods.

While the importance of power is widely accepted, not all practitioners have access to the equipment to measure power output such as a force platform or position transducer. Thus, it is important to examine the validity of the measurements that can be easily administered through typical strength and conditioning programs. For example, testing 1RM for weightlifting exercises is a commonly used test in the practical setting. Previous studies (Baker & Nance, 1999a; Fry & Kraemer, 1991; Fry et al., 1991) suggest the athletes who have higher playing ability have higher performance in power clean. If the reverse is true, (i.e. the athletes who have high performance in weightlifting exercise also have high performance in their sports), 1RM for weightlifting exercises can give practitioners very useful information for monitoring training progression and indicating potential sports performance.

Although there is a consensus that the weighted jump squat is an effective form of training to enhance the capability of power output (Newton et al., 1999; Wilson et al., 1993), practitioners need to consider the risk of injury due to the landing impact during this exercise. In attempting to minimize the landing impact, electromagnetic braking mechanisms have been developed (Humphries et al., 1995). Such braking mechanisms effectively reduce the initial impact force at landing, but the importance of the eccentric phase of weighted jump squat in terms of improvement of athletes' strength qualities and athletic performance has not been thoroughly investigated as yet (Hoffman et al., 2005; Humphries et al., 1995). While undesirable effects of landing impact has been discussed in previous studies (Humphries et al., 1995; Ricard & Veatch, 1990), other studies (Bobbert et al., 1996; Moore & Schilling, 2005; Walshe et al., 1998) suggested the possibility that the eccentric phase of the movement might enhance the performance of the subsequent concentric phase. Therefore, further studies need to investigate the differential effects of weighted jump squat training with and without eccentric braking.

CHAPTER 3

STUDY 1

RELIABILITY OF PERFORMANCE MEASUREMENS DERIVED FROM GROUND REACTION FORCE DATA DURING COUNTERMOVEMENT JUMP AND THE INFLUENCE OF SAMPLING FREQUENCY

Journal of Strength and Conditioning Research, (In Review, August 2007)

Naruhiro Hori, Robert U. Newton, Naoki Kawamori,
Michael R. McGuigan, William J. Kraemer and Kazunori Nosaka

INTRODUCTION

For many sporting movements, the success of performance is largely affected by how much force and power is applied toward objects such as ground, ball, or sporting equipment (Newton & Kraemer, 1994). Thus, possessing the ability of the neuromuscular system to output high force and power and to increase them rapidly from a relatively relaxed muscle state is one of the most important goals for strength and conditioning programs (Baker, 2001a). Such characteristics of the neuromuscular system have been termed “strength qualities” (Newton & Dugan, 2002) and for ground based tasks (e.g. ball games, track and field) in which the leg extensors are predominant, an explosive movement of short durations such as vertical jump is often used to assess these qualities (Hori et al., In press). In particular, the countermovement jump (CMJ) is one of the most common test measurements among scientists and practitioners (Bobbert et al., 1996; Harman et al., 1990; Harman et al., 1991; Reiser, 2006; Sayers et al., 1999). A CMJ typically involves the athlete, keeping their hands on hips or with arm swing, squatting down to about 90° knee bend, and then immediately jumping vertically as high as possible. By measuring force, velocity and power output during CMJ, it is possible to distinguish athletes with high and low leg extensor abilities (Young et al., 2005), examine the effects of a given training intervention (Newton et al., 1999; Wilson et al., 1993), and/or monitor athlete progress during their long term training program (Baker, 2001a). Traditionally, only the jump height during CMJ has been used as the performance outcome. However, more recently research has indicated that it is more insightful to examine a range of characteristics of how the athlete produces this jump height. In this process of strength diagnosis, scientists and practitioners examine these performance variables in an attempt to understand the underlying qualities contributing to the performance (Newton & Dugan, 2002). However, to have confidence in the utility of these measurements for research and athlete monitoring, the reliability of measurement of the variables needs to be assessed in detail.

To measure force, velocity and power output during CMJ, several different methodologies are available (Dugan et al., 2004; Hori et al., 2006). For example, Wilson et al. (1993) used displacement-time data obtained from a position transducer, Newton et al. (1999) used ground reaction force (GRF)-time data obtained from a force platform, and Young et al. (2005) used a combination of displacement-time data obtained from a position transducer and GRF-time data obtained from a force platform to calculate the performance values. Despite a variety of methodologies, it has been suggested that these variables measured directly or calculated from GRF-time data recorded from a force platform is the most accurate way to assess strength qualities during a vertical jump (Hori et al., 2006).

In actual testing situations, force output needs to be measured throughout a certain period (i.e. at least from the beginning to the end of the movement) since the force output varies with time. During the data sampling, how often the signal is sampled each second is termed sampling frequency (McGinnis, 2005). In general, a force platform with a high capacity of sampling frequency is more expensive than that with low capacity. On the other hand, a force platform with high portability usually possesses lower capacity of sampling frequency compared to a force platform permanently mounted in a laboratory. Finally, higher sampling frequency requires larger data files and thus more disk storage space and processing time. As a result there is inconsistency in the research literature as to the sampling frequency used during performance measurement from a force platform. Therefore, determining the effect of and perhaps more importantly what minimum sampling frequency can be used for this form of performance analysis will be important to inform scientists and practitioners when selecting a force platform and sampling frequency.

The purpose of this study was to examine the within session reliability of several variables commonly used to characterize jump performance. Further, the influence of reducing sampling frequency on force, velocity and power values and their reliability with seven different sampling frequencies (500, 400, 250, 200, 100, 50, and 25 Hz) was examined. Measurements describing the shape of force-time curve (peak force, mean force, peak rate of force development [RFD] and time to peak force), velocity-time curve (peak and minimum velocity) and power-time curve (peak power, mean power, average rate of power development [RPD] and time to peak power) were analyzed to assess some commonly used strength diagnosis measures. In theory, the higher the sampling frequency, the more accurate the obtained values are. As commonly cited previous studies (Haff et al., 1997; Harman et al., 1990; Harman et al., 1991; Sayers et al., 1999) sampled GRF-time data at 500 Hz, this sampling frequency was considered as the reference. However, other papers (Hori et al., In press) have reported the data sampled at a frequency of 200 Hz, and thus it is important to assess the validity of such data. Further, scientists and practitioners need information as to the effect of lower frequency of sampling so that they can make informed decisions balancing accuracy with reducing data file sizes and perhaps using cheaper and more portable force platforms.

METHODS

Experimental Approach to the Problem

Twenty four male subjects were recruited into this study. The subjects performed CMJ on a force platform, and GRF-time data were sampled at rate of 500 Hz and stored on a computer hard disk. The data was then re-sampled using interpolation techniques to produce GRF-time data sampled at six different frequencies of 400, 250, 200, 100, 50 and 25 Hz. Prior to the testing, all subjects had one session of familiarization, and practice of CMJ until they felt adequately familiarized. Two trials were recorded for each subject so that within session reliability could be examined. The trials which exhibited the highest peak power value calculated from GRF-time data sampled at 500 Hz were used for statistical analysis.

Subjects

Twenty four male subjects were recruited from the university student population. Most of these subjects were regularly participating in some type of physical activity such as weight training, running, swimming, cycling, and/or ball games (e.g. soccer) two to three times per week on average. Subjects' age, height, and body mass were (mean ± S.D.) 25.0 ± 4.4 yrs, 176.5 ± 7.9 cm, and 79.3 ± 10.7 kg respectively. Prior to the testing session, the subjects rode on a stationary bike for 5 minutes at 100W intensity and 60 rpm for warm up. This study was approved by the University's Human Research Ethics Committee. All subjects read an information letter explaining the procedure of the study, and signed an informed consent document.

Countermovement Jump

During the CMJ, the subjects first stood upright, then squatted to a self selected depth of approximately 90° knee flexion, and jumped immediately as high as possible without pausing. During these jump movements, the subjects kept their hands on hips. The jumps were performed on a force platform (Quattro Jump – Type 9290AD, Kistler, Switzerland) and the vertical component of GRF was sampled at a rate of 500 Hz for 10 seconds using dedicated software (Ballistic Measurement System, Fitness Technology, Australia), and data were saved on the computer hard drive. To control the effects of different filtering techniques on the values, GRF-time data was not filtered in this process (Street et al., 2001). After all data on all subjects were collected, the data files were opened and re-sampled to 400, 250, 200, 100, 50 and 25 Hz using a custom computer program written in VB.NET (Microsoft, Redmond, WA) by interpolating between points to assemble a series of data sets corresponding to these frequencies. Briefly, this software performed the following procedure; three samples were inserted using linear interpolation between every two consecutive samples in the measured force-time data (i.e. 500 Hz), thus producing a new data set with an effective sample frequency of 2000 Hz. Then every 5th, 8th, 10th, 20th, 40th and 50th time point was drawn from this data set to create new sets of data effectively sampled at 400, 250, 200, 100, 50 and 25 Hz. Once seven different GRF-time data sets were obtained, velocity of the system center of gravity (COG) was obtained from each GRF-time data set using the forward dynamics approach. This calculation is based on the relationship that change in momentum is equal to the impulse applied which is the integral (Trapezoid method) of the force time data (Dugan et al., 2004; Hori et al., 2006). Thus, velocity at each time point was calculated from the changes in momentum and the subject's body mass. Data sampling was started when the subject was completely still, so that it was assumed the velocity of COG at the initial time point was 0 m/s.

As summarized Figure 3.1, the beginning of eccentric phase was determined where force started to decrease, the end of eccentric phase (i.e. beginning of concentric phase) was determined where velocity changed from negative to positive, and the end of concentric phase was determined where GRF became 0 N. Power at each time point was calculated as a product of GRF and velocity of COG. Peak power and peak velocity were determined as the highest values during the concentric phase of the jump. Minimum velocity was determined as the lowest value during the eccentric phase. Mean power was determined as the average power output between the following time points; 1) when concentric phase began, and 2) when concentric phase ended. Peak force was defined as the highest force before the take off (i.e. not the impact force at landing). Mean force was the average between the following time points; 1) beginning of concentric phase, and 2) end of concentric phase. Peak RFD was defined as the highest rate of change in GRF over a given 30 ms epoch prior to the take off (Pryor et al., 1994). Time to peak force was defined as the time difference between the following

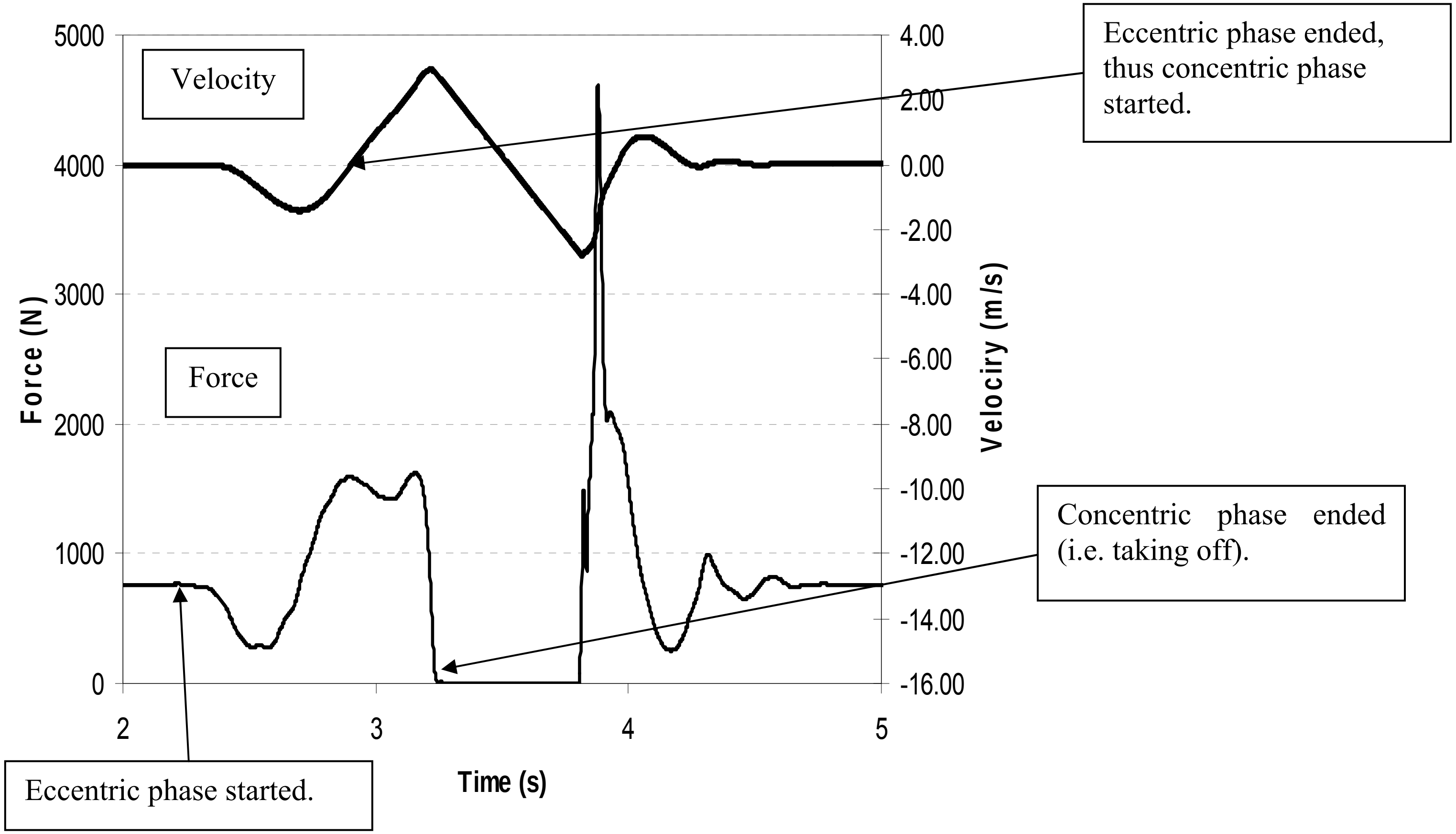

Figure 3.1 Definition of eccentric and concentric phases.

time points; 1) beginning of eccentric phase, and 2) time point when peak force occurred. Time to peak power was defined as the time difference between the following; 1) beginning of concentric phase and 2) time when peak power was produced. Average RPD was obtained from peak power divided by time to peak power (Cormie et al., In Press).

Statistical Analyses

Reliability of measurement was calculated between the two trials using intra-class correlation coefficients (ICC), and ICC > 0.70 was considered as a minimum acceptable reliability (Baumgartner & Chung, 2001). In addition, coefficient of variance (CV) was also calculated. The influences of sampling frequency on the dependent variables were examined by percentage difference between reference 500Hz and each lower frequency data set. Percentage differences for each variable from each data set were obtained as means of each individual's percentage difference, so that standard deviation of percentage difference was also calculated. Since the purpose of the present study was to provide readers the magnitude of error due to the reduced sampling frequencies, percentage differences from referenced values have been reported instead of statistical significance. If pair wise comparison is made using probability statistical techniques (e.g. paired samples T-test, or repeated measures one-way analysis of variance), even practically trivial difference can be detected as significance. However, the focus of this study is not whether the difference is statistically significant but rather whether such differences are practically meaningful or not. Pearson's product moment correlation between values obtained from 500 Hz and other sampling frequencies were also calculated to determine if the effect of reduced sampling frequency was linear and systematic or not. Strength of correlation was interpreted as r > 0.9 is nearly perfect, 0.7-0.9 is very high, 0.5-0.7 is high, 0.3-0.5 is moderate, 0.1-0.3 is small, 0.1 or less is trivial (Hopkins, 2002).

Table 3.1 Reliability of measurements. ICC: Intraclass correlation coefficient, CV: Coefficient of variation, RFD: Rate of force development, and RPD: Rate of power development.

	Peak Power		**Mean Power**		**Peak Force**		**Mean Force**		**Peak Velocity**	
	ICC	**CV**	**ICC**	**CV**	**ICC**	**CV**	**ICC**	**CV**	**ICC**	**CV**
500 Hz	0.98	2.3	0.84	7.8	0.92	4.1	0.93	3.9	0.98	1.3
400 Hz	0.98	2.3	0.84	8.3	0.92	4.1	0.93	4.0	0.98	1.3
250 Hz	0.98	2.3	0.77	8.9	0.92	4.1	0.90	4.4	0.98	1.3
200 Hz	0.98	2.3	0.85	7.4	0.92	4.1	0.94	3.7	0.98	1.3
100 Hz	0.97	2.7	0.82	7.9	0.92	4.1	0.92	3.9	0.98	1.3
50 Hz	0.98	2.6	0.74	9.8	0.92	4.1	0.88	5.0	0.98	1.3
25 Hz	0.96	3.3	0.71	12.3	0.93	3.9	0.84	6.3	0.95	1.7

	Minimum Velocity		**Peak RFD**		**Time to Peak Force**		**Average RPD**		**Time to Peak Power**	
	ICC	**CV**	**ICC**	**CV**	**ICC**	**CV**	**ICC**	**CV**	**ICC**	**CV**
500 Hz	0.78	9.8	0.66	24.0	0.75	11.4	0.91	8.2	0.85	7.0
400 Hz	0.78	9.7	0.66	24.0	0.74	11.8	0.92	8.1	0.85	6.8
250 Hz	0.78	9.8	0.69	23.0	0.76	11.3	0.92	7.9	0.85	6.8
200 Hz	0.78	9.8	0.66	24.0	0.78	10.8	0.92	8.5	0.83	7.2
100 Hz	0.78	9.7	0.67	23.5	0.75	11.6	0.91	8.6	0.84	7.5
50 Hz	0.78	9.7	0.75	20.7	0.75	12.3	0.95	8.0	0.83	7.1
25 Hz	0.75	10.0	0.75	22.2	0.74	13.4	0.87	14.9	0.57	14.4

RESULTS

Visual inspection of power, force, and velocity data plotted against time for any trial with reduced sampling frequency data appeared to completely overlay the reference 500Hz data. While most measurements exhibited high reliability across the entire range of sampling frequencies, peak RFD and time to peak power did not meet minimum acceptable ICC at several sampling frequencies (Tables 3.1). Percent difference from the reference value for each measurement is plotted as Figures 3.2, 3.3 and 3.4. It can be observed from these figures that there is a breakpoint in accuracy at less than 200 Hz where percentage differences from the referenced values suddenly increase in most of the measurements. However, for all variables calculated from reduced sampling frequency data, there were nearly perfect or very high correlations between values across all measurements and sampling frequencies.

DISCUSSION

The main purpose of the present study was to determine the measurement reliability of key performance measures commonly used to quantify strength qualities of CMJ from GRF data. As presented in Table 3.1, most values appeared to be reliable across a range of sampling frequencies except for peak RFD and time to peak power. Particularly, peak power, peak force and peak velocity were highly reliable (ICC = 0.92-0.98, CV = 1.3-4.1) regardless of sampling frequency. Further, we examined effects of different sampling frequencies on validity of CMJ performance measures. It is apparent that 200 Hz is somewhat of a breaking point where error due to the reduced sampling frequencies suddenly increases in magnitude for several measurements (Figure 3.2, 3.3 and 3.4). Obviously, it would be a problem if true difference between two test occasions or two groups is hidden within the error due to reduced sampling frequency. That is, the fundamental question is how much is the true difference that scientists and practitioners are trying to detect. For example, Newton et al. (1999) reported changes in peak power output values during CMJ as a result of 8 weeks of weighted jump squat training was 8.0% in their longitudinal study using highly competitive men’s volleyball players. Young et al. (2005) reported starters output 16.1% higher peak power during CMJ than non-starters in a professional Australian Rules football club. As observed in Figures 3.2, 3.3 and 3.4, if sampling frequency was 200 Hz or higher, percentage differences to the referenced values were less than ± 2% in all measurements, which is far smaller than the difference reported in previous studies (Newton et al., 1999; Young et al., 2005).

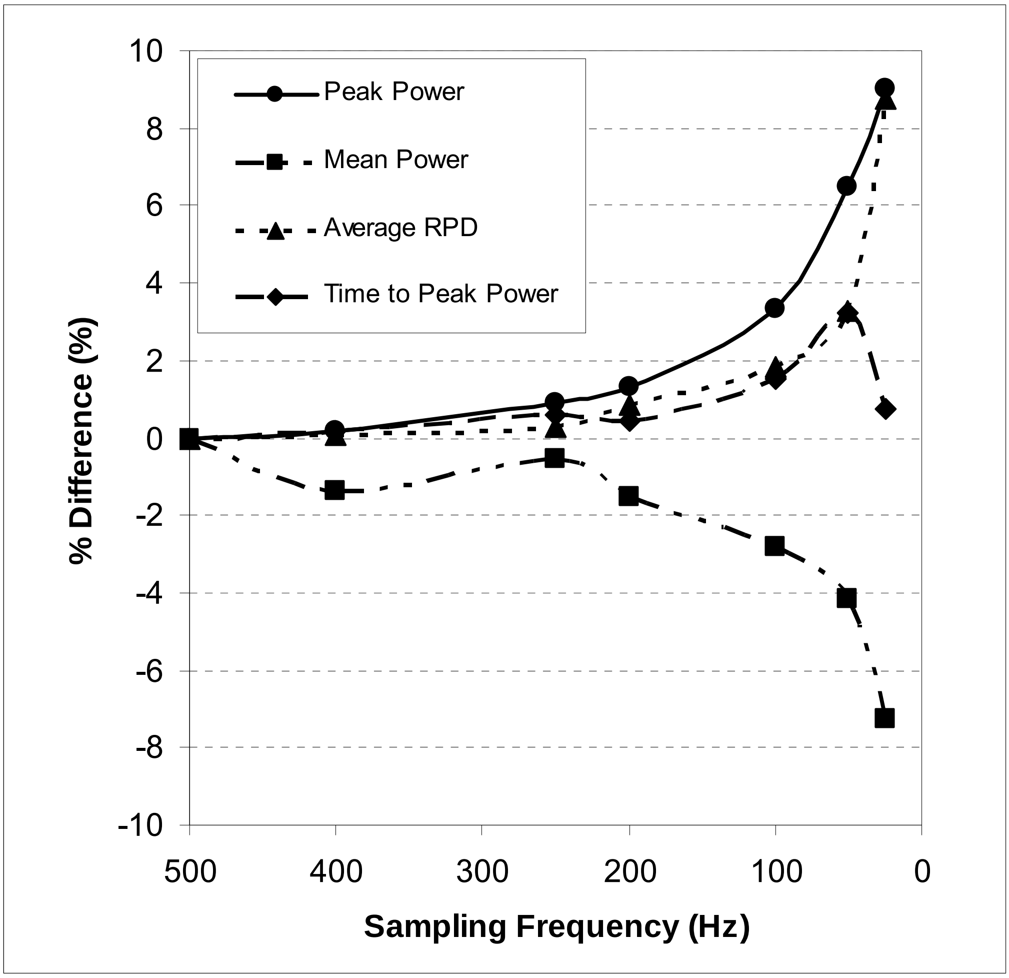

Figure 3.2 Percentage difference between power and related variables derived from the reference 500Hz data and successively lower sample rates. RPD is rate of power development.

Sampling theorem generally dictates that frequency of data measurement should be at least twice that of the signal of interest, which is known as the Nyquist criterion (Derrick, 2004). For example, it is recommended to sample data at 20 Hz or higher for human locomotion (Derrick, 2004) for which the fastest movements are less than 10Hz, so that even 25 Hz satisfies this criterion. In reality, it is recommended that the sample frequency should be at least 5-10 times the frequency of the signal of interest or 50 to 100Hz for human movements (Derrick, 2004).

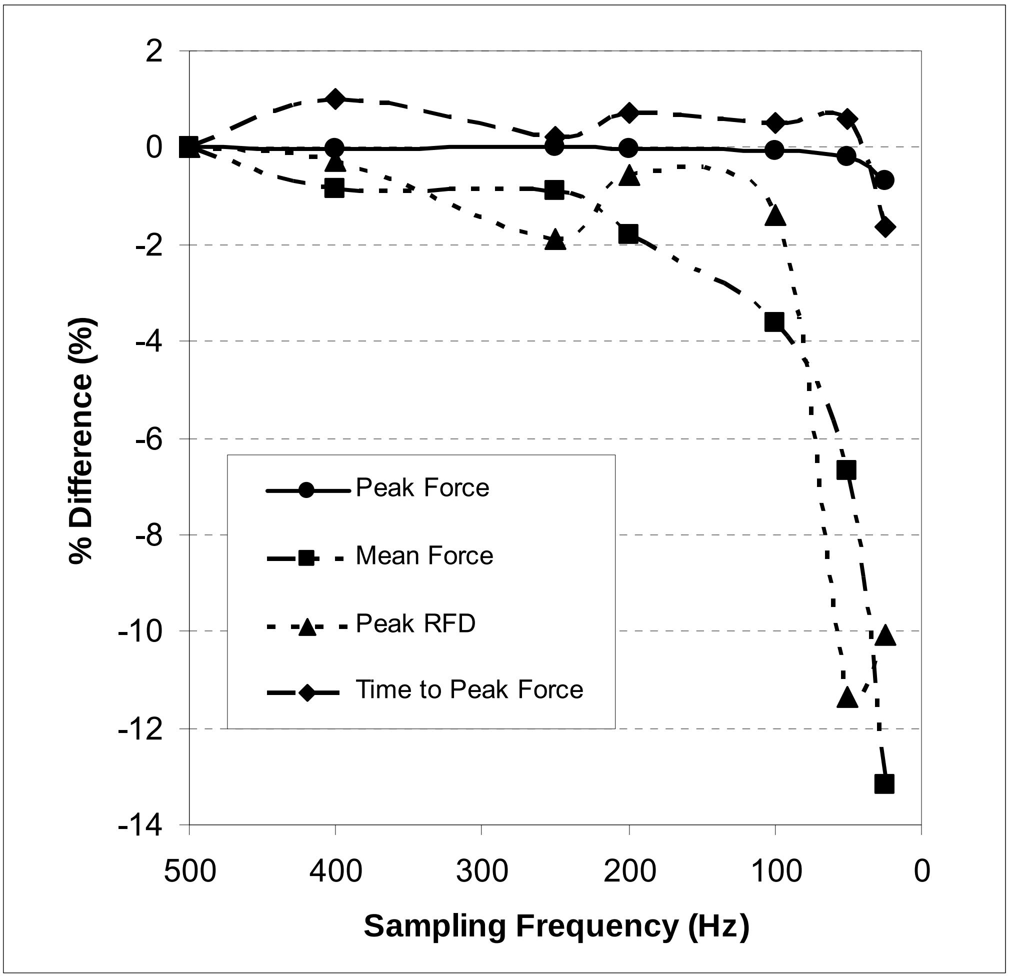

Figure 3.3 Percentage difference between force and related variables derived from the reference 500Hz data and successively lower sample rates. RFD is rate of force development.

Peak power values appeared to be highly reliable. Importantly, in considering ICC and CV, peak power seems a more reliable value than mean power (Table 3.1). As presented in Table 3.2 and 3.3, there is some degree of difference between the reference values and values calculated from reduced sampling frequencies up to 9.03% in peak power, and -7.28% in mean power while whether such differences are meaningful or not is dependent on the purpose of measurement. It is important to note that peak power values tended to be overestimated when sampling frequency is reduced. It is speculated that this overestimation might be because changes in force between the time points where peak power appears and one prior was concave rather than linear, thus impulse between these two time points was overestimated when the trapezoid method is applied for integration. Conversely, mean power appeared to be underestimated compared to the reference value as sampling frequency is reduced. However, it is important to note

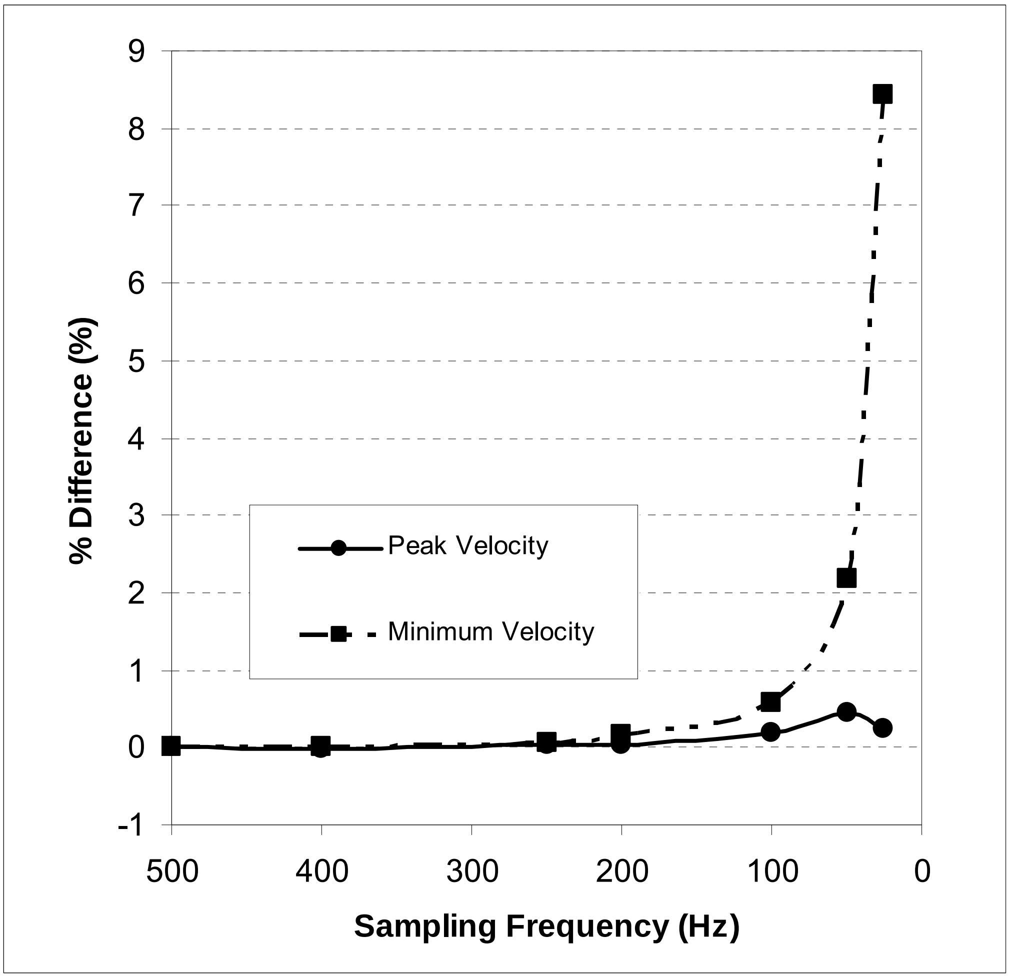

Figure 3.4 Percentage difference between velocity variables derived from the reference 500Hz data and successively lower sample rates.

standard deviation of percentage difference in mean power (2.72-9.40%) was much larger than that of peak power (0.06-3.86%). When individual data is examined, peak power was overestimated in all subjects when sampling frequency is reduced, but mean power was overestimated in some subjects and underestimated in other subjects. Also, it is important to note that the two time points need to be determined manually to calculate mean power, mean force, time to peak force, average RPD, and time to peak power. If sampling frequency is reduced, the sensitivity of determining the time related values is reduced, thus CV in some of these measurements were suddenly enlarged when sampling frequency was 50 or 25 Hz (Tables 3.1).

Table 3.2 Peak power calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (W)	S.D. (W)	% difference	S.D. (%)	Pearson's r
500 Hz	4299	685			
400 Hz	4308	686	0.20	0.06	1.00
250 Hz	4338	694	0.89	0.24	1.00
200 Hz	4356	697	1.31	0.26	1.00
100 Hz	4444	716	3.34	0.66	1.00
50 Hz	4582	754	6.51	1.63	1.00
25 Hz	4694	808	9.03	3.86	0.98

Table 3.3 Mean power calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (W)	S.D. (W)	% difference	S.D. (%)	Pearson's r
500 Hz	1889	344			
400 Hz	1864	346	-1.35	2.72	0.99
250 Hz	1876	330	-0.56	3.69	0.98
200 Hz	1858	334	-1.50	3.96	0.98
100 Hz	1838	353	-2.80	4.25	0.98
50 Hz	1808	345	-4.18	6.65	0.92
25 Hz	1752	381	-7.28	9.40	0.87

When force is applied toward the force platform, it is apparent that the GRF can vary over time. Although force is applied over a period of time, GRF is recorded only at the time points determined by sampling frequency (e.g. every 0.002 s if sampling frequency is 500 Hz). In other words, a continuously varying phenomenon is being measured at discrete time points with the assumption that change between successive samples is linear. If changes in force are too rapid to record at the given sampling frequency, the changes in force occurring between two consecutive samples will not be accurately represented. Thus, the rapid change in force could be missed when GRF was sampled at lower frequencies (i.e. longer duration between two time points sampled), such as 50 or 25 Hz (Tables 3.4 and 3.5).

Power is obtained from GRF multiplied by instantaneous velocity at each time point. As well as the differences in GRF across the range of sampling frequencies, the differences in velocity values between different sampling frequencies were another reason why there were differences in power values. Using the forward dynamics approach, instantaneous velocity is determined from changes in momentum over the sample period (i.e. 1 / sampling frequency). Changes in momentum occur only as a result of force applied over this period, so it is impossible to determine the instantaneous velocity from any single time point. To determine the changes in momentum over a period of time, impulse is obtained by integration of the GRF-time curve. In the process of integration, there is a possible source of error if the force curve between consecutive time points is not a straight line. As a result, power output values may be overestimated or underestimated. Particularly, the rapid changes in GRF cannot be accurately integrated if sampling frequency is too low (Street et al., 2001). This could be the reason why the magnitude of error became larger as sampling frequencies became lower (Tables 3.6 and 3.7).

Peak RFD and time to peak force were measured to examine whether there was any influence of reducing sampling frequencies on shape of the force-time curve. The reliability of peak RFD did not meet the minimum acceptable ICC even obtained from 500 Hz (Table 3.1). It is important to note that the rapid force development in CMJ is produced during the eccentric phase, and a good jumper can keep exerting high force rapidly (Reiser, 2006). Therefore, peak RFD may appear during the eccentric phase for some, and during the concentric phase for others, depending on each subject's jump technique (e.g. how rapidly and how deep he/she squats during the eccentric phase,

Table 3.4 Peak force calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (N)	S.D. (N)	% difference	S.D. (%)	Pearson's r
500 Hz	1836	306			
400 Hz	1836	306	-0.01	0.02	1.00
250 Hz	1836	306	0.00	0.02	1.00
200 Hz	1835	305	-0.03	0.06	1.00
100 Hz	1835	305	-0.06	0.09	1.00
50 Hz	1832	306	-0.20	0.27	1.00
25 Hz	1824	304	-0.68	0.61	1.00

Table 3.5 Mean force calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (N)	S.D. (N)	% difference	S.D. (%)	Pearson's r
500 Hz	1408	204			
400 Hz	1395	202	-0.85	1.22	1.00
250 Hz	1395	201	-0.88	1.91	0.99
200 Hz	1382	198	-1.80	1.67	0.99
100 Hz	1357	201	-3.63	2.13	0.99
50 Hz	1314	196	-6.67	3.39	0.97
25 Hz	1222	190	-13.17	5.06	0.92

Table 3.6 Peak velocity calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (m/s)	S.D. (m/s)	% difference	S.D. (%)	Pearson's r
500 Hz	2.79	0.24			
400 Hz	2.79	0.24	-0.03	0.10	1.00
250 Hz	2.79	0.24	0.03	0.20	1.00
200 Hz	2.79	0.24	0.04	0.11	1.00
100 Hz	2.80	0.24	0.19	0.18	1.00
50 Hz	2.81	0.24	0.44	0.57	1.00
25 Hz	2.80	0.22	0.23	0.23	0.99

Table 3.7 Minimum velocity calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (m/s)	S.D. (m/s)	% difference	S.D. (%)	Pearson's r
500 Hz	-1.20	0.18			
400 Hz	-1.20	0.18	0.00	0.00	1.00
250 Hz	-1.20	0.18	0.05	0.33	1.00
200 Hz	-1.20	0.18	0.15	0.31	1.00
100 Hz	-1.19	0.18	0.57	0.45	1.00
50 Hz	-1.17	0.17	2.18	1.21	1.00
25 Hz	-1.10	0.17	8.42	4.41	0.96

how much force he/she generates during concentric phase). In the present study, depth and tempo of squatting were not restricted. As a result, peak RFD values of some subjects could appear during eccentric phase, and that of other subjects could appear during concentric phase. Such inconsistency might be the reason why reliability of peak RFD was low and standard deviation of this measurement was large. Normally, peak RFD is determined during a squat jump which is concentric only to minimize these reliability issues.

In the present study, time to peak power and average RPD were measured to examine whether there was any influence of reducing sampling frequency on shape of the power-time curve. As a next step, since the present study confirmed these measurements as reliable, future research should examine the importance of average RPD. While many studies have reported the peak power and/or mean power, only one study (Cormie et al., In Press) has reported the shape of power-time curve described by average RPD to date. As this is a novel performance diagnosis measure it was decided to include it in the current study. Cormie et al. (In Press) examined the influence of external load on average RPD during CMJ and weighted jump squat and reported significant effects. In future studies, relationships to athletic performance (e.g. vertical jump height, sprint time, or playing division), and/or adaptation to training intervention of average RPD would be of interest for scientists and practitioners. Based on our findings, RPD is reliable and relatively easy to determine from GRF data.

In summary, the present study examined the reliability of performance qualities measured from GRF data using the forward dynamics approach during CMJ as well as the influence of sampling frequency on these values. While peak power, peak force and peak velocity exhibit especially high reliability, all but two values (peak RFD and time to peak power) satisfied a minimum acceptable reliability (Table 3.1). Although there were differences up to 13.7% between values obtained from reference (500 Hz) and 400 Hz or lower sampling frequency in some measurements, the present study also found nearly perfect or very high correlation in all measurements indicating the effect of reduced sampling frequency on these measures is highly linear and systematic (Tables 3.2-3.11). When sampling frequencies and percentage differences were plotted, it was noted the differences markedly increased at 100 Hz in peak power, mean power and mean force (Figures 3.2, 3.3 and 3.4). On the other hand, if sampling frequency is 200 Hz or higher, ranges in percentage differences were less than ±2% in all measurements

Table 3.8 Peak rate of force development calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (N/s)	S.D. (N/s)	% difference	S.D. (%)	Pearson's r
500 Hz	8757	3879			
400 Hz	8733	3874	-0.27	0.30	1.00
250 Hz	8591	3803	-1.88	1.04	1.00
200 Hz	8707	3872	-0.57	0.61	1.00
100 Hz	8639	3854	-1.41	1.37	1.00
50 Hz	7761	3399	-11.37	4.86	0.99
25 Hz	7898	3703	-10.09	6.35	0.99

Table 3.9 Time to peak force calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (ms)	S.D. (ms)	% difference	S.D. (%)	Pearson's r
500 Hz	0.686	0.181			
400 Hz	0.692	0.177	1.01	1.75	1.00
250 Hz	0.688	0.182	0.24	2.04	1.00
200 Hz	0.690	0.178	0.71	2.03	1.00
100 Hz	0.690	0.182	0.50	1.87	1.00
50 Hz	0.691	0.185	0.60	2.62	1.00
25 Hz	0.678	0.195	-1.65	5.41	0.98

Table 3.10 Average rate of power development calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (W/s)	S.D. (Ws)	% difference	S.D. (%)	Pearson's r
500 Hz	19608	6897			
400 Hz	19612	6802	0.10	0.64	1.00
250 Hz	19663	6899	0.28	0.72	1.00
200 Hz	19759	6798	0.87	0.91	1.00
100 Hz	19988	7080	1.83	2.10	1.00
50 Hz	20210	6817	3.30	3.41	1.00
25 Hz	21372	7602	8.74	8.40	0.98

Table 3.11 Time to peak power calculated from ground reaction force data sampled at progressively lower frequencies.

	Mean (ms)	S.D. (ms)	% difference	S.D. (%)	Pearson's r
500 Hz	0.230	0.040			
400 Hz	0.230	0.039	0.19	0.70	1.00
250 Hz	0.231	0.040	0.61	0.72	1.00
200 Hz	0.231	0.039	0.44	1.02	1.00
100 Hz	0.233	0.041	1.52	2.06	0.99
50 Hz	0.237	0.040	3.22	3.96	0.98
25 Hz	0.232	0.046	0.77	7.74	0.93

which is far smaller than the changes that scientists and practitioners would meaningfully be interested in. As a result, the following practical application was concluded.

PRACTICAL APPLICATIONS

First of all, this study confirmed peak power, peak force and peak velocity are highly reliable measurements when recorded during CMJ and calculated using a force plate and GRF. Therefore, scientists and practitioners are encouraged to consider this methodology and these variables as valid and reliable measures to quantify athlete performance. In addition, average RPD also appears to be reliable, thus future investigation should examine the usefulness of this novel measurement. On the other hand, reliability of peak RFD and time to peak power were not sufficient. Insufficient reliability of peak RFD could be due to the variance of technique of CMJ between subjects. Thus, if scientists and practitioners are particularly interested in this measurement, it seems necessary to restrict and standardize subjects' movement pattern (e.g. range of motion of countermovement) or use a concentric only jump test. For example, Wilson et al. (1995) utilized a Smith machine with mechanical stops to control the depth of countermovement. However, such restricted movement is less specific to typical tasks in sport and so validity of such methodology may need to be carefully considered.

Theoretically, scientists and practitioners are recommended to use a force platform with the highest possible sampling frequency. However, in considering acceptable reliability, less than 2% difference to the reference values in all measurements, and nearly perfect correlation, scientists and practitioners may consider the use of sampling frequencies as low as 200 Hz if necessary. In general, force platforms with higher portability are accompanied with lower sampling frequency. In many instances scientists and practitioners use force platforms at the actual training site rather than the laboratory and thus portability of equipment is an important issue to be considered. Also, lower sampling frequency with reduced disk storage space is helpful to scientists and practitioners when they transfer sampled data using e-mail or USB external drive. Most importantly, scientists and practitioners need to keep sampling frequency consistent at all testing occasions no matter which sampling frequency is selected to allow valid comparison of performance variables across time.

CHAPTER 4

STUDY 2

COMPARISON OF FOUR DIFFERENT METHODS TO MEASURE POWER OUTPUT DURING THE HANG POWER CLEAN AND THE WEIGHTED JUMP SQUAT

Journal of Strength and Conditioning Research, 2007, 21(2), 314-320

Naruhiro Hori, Robert U. Newton, Warren A. Andrews, Naoki Kawamori,
Michael R. McGuigan and Kazunori Nosaka

INTRODUCTION

Power is the mechanical quantity defined as the rate of doing work, and obtained as work divided by time or force times velocity (Newton & Kraemer, 1994). For a given task, the success of performance is largely affected by how much power is applied toward objects (e.g. ground, ball, or sporting equipment). Thus, improving power output during sports performance is one of the most important goals for strength and conditioning programs (Baker, 2001a). To maximize the power output during specific movements in sport, a strength and conditioning program should incorporate a long term strategy (Plisk & Stone, 2003). For example, the emphasis of a program may shift from one phase to the next phase targeting capabilities of maximum force output (i.e. maximum strength), maximum power output, or power output against relatively light loads. To monitor the changes in the athlete's capability of power output during a given task at a given load, it is meaningful to measure power output frequently, at least before and after each training phase (Baker, 2001a; Hori et al., 2006; Newton & Dugan, 2002). While the training modality should satisfy the needs of the sports for which one is training (i.e. muscle groups involved, characteristics of force-time curve, form of muscle action: concentric, eccentric or isometric, energy system utilized, and so on), it seems important that the form of testing should be close to the form of training to monitor the athlete's progress. For this reason, considerable research attention has been directed at measuring power output during common resistance training exercises such as hang power clean and weighted jump squat (Baker & Nance, 1999a; Haff et al., 1997; Kawamori et al., 2005; Newton et al., 1999; Stone et al., 2003a; Young et al., 2005). There are several methods to measure power output, and the following four methods are commonly utilized in recently reported research (Dugan et al., 2004; Hori et al., 2006).

- Method 1: From displacement-time data of barbell movement, power applied to the barbell is obtained using inverse dynamics approach (Baker et al., 2001a; Moore et al., 2003).
- Method 2: From ground reaction force (GRF)-time data, power applied to the system (barbell + body) is obtained using forward dynamics approach (Haff et al., 1997; Kawamori et al., 2005).
- Method 3: From displacement-time data of the barbell, power applied to the system (barbell + body) is obtained using inverse dynamics approach (Baker & Nance, 1999a; Baker et al., 2001b; Stone et al., 2003a).

- Method 4: From both displacement-time data of the barbell and GRF-time data, power applied to the system (barbell + body) is obtained as the barbell velocity × GRF (Chiu et al., 2003; Winchester et al., 2005; Young et al., 2005).

Although past studies (Baker & Nance, 1999a; Haff et al., 1997; Kawamori et al., 2005; Newton et al., 1999; Stone et al., 2003a; Young et al., 2005) utilized one of these methods to calculate power output during resistance training exercises, no studies have ever examined if there are any differences in the power output values obtained from the different methods during a given task. Method 1 and 2 are logically valid even when the COG of the barbell and that of the system do not move in parallel, but validity of Method 3 or 4 would depend on whether the COG of the barbell and that of the system move in parallel or not. In the weighted jump squat, previous studies (Baker & Nance, 1999a; Baker et al., 2001b; Chiu et al., 2003; Stone et al., 2003a; Young et al., 2005) assumed that the COG of the barbell and that of the system move in parallel. However, it is obvious that the COG of the barbell and that of the system do not move in parallel during weightlifting exercises, such as snatch, clean, jerk and variations of these exercises (Hori et al., 2006). For this reason, Methods 3 and 4 have been used in previous research measuring power output during weighted jump squat (Baker & Nance, 1999a; Baker et al., 2001b; Chiu et al., 2003; Stone et al., 2003a; Young et al., 2005), but not during the weightlifting exercises except for one study which used Method 4 to measure power output during power clean from the floor (Winchester et al., 2005). Given the increasing use of power measurement to assess performance changes and provide feedback to the athlete and coach, it is important to assess the common methods utilized during two of the most commonly measured movements so as to elucidate reliability, validity and methodological issues of these techniques. Further, some studies report mean power (Baker & Nance, 1999a; Baker et al., 2001a, 2001b) and others peak power (Haff et al., 1997; Kawamori et al., 2005; Newton et al., 1999; Stone et al., 2003b; Winchester et al., 2005; Young et al., 2005) so it would be instructive to compare these measures across movement and measurement techniques.

The purposes of this study were to: (a) examine if there is any difference between the power output values obtained from Method 3 and 4 and the value obtained from Method 2; (b) examine the relationships between the power applied to the barbell and the power applied to the system during hang power clean and weighted jump squat; and (c) examine the relationships between peak and mean power values obtained from each method. First, it was hypothesized that Methods 2, 3 and 4 would exhibit similar power output values during the weighted jump squat, but the values obtained from Methods 3 and 4 during the hang power clean would be quite different from the value obtained from Method 2. Second, if the ability to apply power to the system largely influences the ability to apply power to the barbell, the power output values obtained from Methods 1 and 2 would be significantly correlated. Since a position transducer is generally less expensive and easier to transport than a force platform, the position transducer may be considered as a reasonable alternative to the force platform if the values obtained from Methods 1 and 2 are well correlated (Hori et al., 2006). Third, it was hypothesized that the peak and mean power values would be closely correlated and thus scientists and practitioners could use either measure as a performance indicator. In general, mean power values obtained from the concentric phase are believed more reliable (Hori et al., 2006). However, this requires determination of exact start and end points of the concentric phase which can be somewhat arbitrary with small errors resulting in significant changes in resulting mean power. It is much more exact and faster to obtain peak power measurements and if peak and mean power essentially reflect the same performance capability, it would be recommended to measure peak power.

METHODS

Experimental Approach to the Problem

Thirty subjects performed hang power clean and weighted jump squat on a force platform with a linear position transducer attached to the barbell. The vertical component of GRF and the displacement of the barbell were sampled simultaneously. The power applied to the barbell was calculated using Method 1, the power applied to the system (barbell + body) was calculated using Methods 2, 3 and 4. Peak and mean power (Method 1: power applied to the barbell, Method 2, 3 and 4: power applied to the system) as well as peak velocity (Method 1, 3 and 4: velocity of the barbell, Method 2: velocity of the COG of the system) and peak force (Method 1: force applied to the barbell, Methods 2, 3 and 4: force applied to the system) obtained from these four methods were compared. In addition, to examine the relationships between peak and mean power applied to the barbell and that applied to the system (barbell + body), the correlations between values obtained from Methods 1 and 2 were calculated.

Subjects

Thirty men were recruited from a semiprofessional Australian Rules football team. Their age, height, body mass and one repetition maximum (1RM) hang power clean were (mean ± SD), 21.3 ± 2.7 y, 181.6 ± 6.3 cm, 84.0 ± 8.3 kg and 75.3 ± 8.6 kg respectively. The subjects had at least three months of experience in performing resistance training exercises such as hang power clean and squat at the time of data collection. None of the subjects had any illness or injuries which would affect the test results. This study was conducted during January and February 2006. These months were the off season between their 2005 and 2006 seasons. This study was approved by the University's Human Research Ethics Committee. All subjects read the information letter explaining the procedure of the study, and signed the informed consent document.

Tests and the Order

The testing was administered on three different days, and each test day was separated by at least 48 hours to minimize the effects of fatigue. The order of test measurements was as follows:

- Day 1: Weighted jump squat with 40 kg;
- Day 2: 1RM hang power clean;
- Day 3: Hang power clean with 70% of 1RM load.

Test Procedures

On day 1, subjects performed jump squats with countermovement with a 40-kg barbell carried across the shoulders. Subject's feet position and grip width were self selected. The barbell was placed on their upper trapezius, immediately below C7. They squatted down to a self selected depth (typically 90° knee flexion), and then immediately jumped as high as possible. The subjects performed the weighted jump squat twice, and the average of peak velocity, peak force, peak and mean power values of the two repetitions were used for statistical analysis. Intra-class correlation coefficient (ICC) and coefficient of variation (CV) were calculated from the two repetitions and presented in Tables 4.1 and 4.2. The rationale for selecting this load was: 1) this load has been used previously when testing professional Australian Rules football players (Young et al., 2005); and 2) 40 kg had been the load most frequently utilized during weighted jump squat training by the subjects and so they were accustomed to jumping with this load.

On day 2, 1RM hang power clean was tested. The hang power clean was started from a position in which the subject was standing holding the barbell in front of his body. The subjects began the movement by lowering the barbell to above their knees. From this position, the subjects lifted the barbell upward explosively, and brought the barbell to their shoulders in one movement (Kawamori et al., 2005). Subjects' 1RM was estimated from recent training histories. Based on this estimated 1RM, the weights to be lifted during a series of warm-up sets was determined. In each set, subjects performed 1-3 repetitions, and the weight was increased after each set. Subjects started the warm-up set with the bar only (20 kg), 20-40 kg was added each set until the load was about 60% of estimated 1RM and then 5-10 kg was added until the load was 90% of estimated 1RM. After these sets were completed, the weight was increased by 2.5 or 5 kg after each set until their 1RM was determined.

On day 3, subjects performed the hang power clean using 70% of 1RM load. The barbell was placed on the 40-cm pulling blocks. The subject picked the barbell up from the blocks, and performed the hang power clean as described above. Data sampling was started after the barbell was lifted off the pulling blocks. The subjects performed the hang power clean twice, and the average of peak velocity, peak force, and peak and mean power values of the two repetitions were used for statistical analysis. ICC and CV were calculated from the two repetitions and presented in Tables 1 and 2. The selection of this load was based on the report that the power output during the hang power clean was maximized at around 70% of 1RM load (Kawamori et al., 2005). Additionally, 70% of 1RM has been the load most frequently utilized during hang power clean training by the subjects.

Hang power clean and weighted jump squat were performed on a force platform (Performance Plate, Fitness Technology, Adelaide, Australia) and a linear position transducer (PT5A-150-V62-UP-IK-C25, Celesco, Canoga Park, CA) was attached to the barbell. Vertical component of GRF and displacement of the barbell were sampled simultaneously at 200 Hz for 5 s using computer software (Ballistic Measurement System, Innervations, Perth, Australia), and the vertical component of power output was obtained using the four different methods. *Method 1*: To obtain the velocity-time data of the barbell, the displacement-time data of the barbell was smoothed using a Butterworth 4th order digital low-pass filter with a cut-off frequency of 16 Hz prior to

Table 4.1 Intra-class correlation coefficient of the measurements. HPC = hang power clean, and WJS = weighted jump squat.

		Method 1	Method 2	Method 3	Method 4
HPC	Peak Velocity	0.89	0.86	0.89	0.89
	Peak Force	0.62	0.89	0.89	0.89
	Peak Power	0.67	0.90	0.71	0.89
	Mean Power	0.74	0.90	0.66	0.91
WJS	Peak Velocity	0.84	0.96	0.84	0.84
	Peak Force	0.71	0.94	0.58	0.94
	Peak Power	0.79	0.97	0.65	0.91
	Mean Power	0.70	0.89	0.70	0.89

Table 4.2 Coefficient of variation of the measurements. HPC = hang power clean, and WJS = weighted jump squat.

		Method 1	Method 2	Method 3	Method 4
HPC	Peak Velocity	3.1	4.5	3.1	3.1
	Peak Force	15.1	4.7	15.4	4.7
	Peak Power	13.9	6.0	14.9	6.2
	Mean Power	12.4	7.9	15.3	6.7
WJS	Peak Velocity	2.5	1.2	2.5	2.5
	Peak Force	2.7	1.8	9.0	4.7
	Peak Power	4.0	1.8	10.4	3.3
	Mean Power	6.8	3.6	11.1	3.9

differentiation using finite difference technique. To obtain barbell acceleration-time data, displacement-time data of the barbell was smoothed using a Butterworth 4th order digital low-pass filter with a cut-off frequency of 10 Hz prior to double differentiation using finite difference technique. Force applied to the barbell was obtained as the barbell mass × barbell acceleration + barbell weight (barbell mass × g, where g = -9.81m.s^{-2}) at each time point. To obtain power applied to the barbell, the force applied to the barbell was multiplied by the velocity of the barbell at each time point. *Method 2*: Velocity of the COG of the system (barbell + body) was calculated from GRF-time data based on the relationship between impulse and momentum in which impulse is equal to the changes in momentum (forward dynamics approach) (Dugan et al., 2004; Hori et al., 2006). Power applied to the system was calculated as the product of velocity of the COG of the system and GRF at each time point. *Method 3*: The velocity and acceleration of the barbell were obtained as described in method 1. Force applied to the system was obtained as the system mass (i.e. barbell mass + body mass) × barbell acceleration + system weight ([barbell mass + body mass] × g, where g = -9.81m.s^{-2}) at each time point. To obtain power applied to the system, the force applied to the system was multiplied by the velocity of the barbell at each time point. *Method 4*: Displacement-time and velocity time data for the barbell were obtained as described in Method 1. Power applied to the system was obtained as GRF × barbell velocity at each time point.

In all four methods, peak power and mean power (Method 1: power applied to the barbell, Methods 2, 3 and 4: power applied to the system [barbell + body]) as well as peak velocity (Methods 1, 3 and 4: velocity of the barbell, Method 2: velocity of the COG of the system), and peak force (Method 1: force applied to the barbell, Methods 2, 3 and 4: force applied to the system) were obtained. The mean power was determined as the average of the concentric phase. The beginning of concentric phase was defined as the time point where the direction of displacement (Methods 1, 3 and 4: displacement of the barbell, method 2: displacement of the COG of the system) changed from downward (eccentric phase) to upward (concentric phase) at which the velocity (Methods 1, 3 and 4: velocity of the barbell, Method 2: velocity of the COG of the system) became 0 m/s (i.e. power became 0 W). The end of concentric phase was defined as the time point where the acceleration of the barbell became -9.81 m/s^2 in Methods 1 and 3, and the GRF became 0 N in Methods 2 and 4. However, during the hang power clean, some of the subjects' feet were not projected into the air even if they finished their concentric muscle action of hip, knee and ankle extension. If this was the case, the acceleration of the barbell did not reach -9.81 m/s^2 in Methods 1 and 3, and GRF did not become 0 N in Methods 2 and 4. Therefore, the completion of concentric phase was determined as the time point where acceleration of the barbell (in Methods 1 and 3) or GRF (in Methods 2 and 4) were at minima.

Statistical Analyses

Mean ± SD was calculated using standard methods. In each exercise, the peak velocity, peak force, peak power and mean power values obtained from the four methods were compared using one-way analysis of valiance (ANOVA) with Tukey's post-hoc test. Pearson's product moment correlation coefficients were obtained to examine the relationships between the peak and mean power values obtained from the four methods. In addition, Pearson's product moment correlation coefficients between peak and mean power values obtained from each method were calculated. Criterion alpha level for significance was set at $p \leq 0.05$ for all analyses.

RESULTS

The comparison of values obtained from the four Methods is presented in Table 4.3 and relationships between peak and mean power values obtained from different methods appear in Tables 4.4 and 4.5. The relationships between peak and mean power values obtained from each method are presented in Table 4.6. In addition, the displacement-time curve, velocity-time curve, force-time curve, and power-time curve of representative subjects in the hang power clean (Figures 4.1, 4.2, 4.3 and 4.4) and the weighted jump squat (Figures 4.5, 4.6, 4.7 and 4.8) are presented. Although data were sampled for 5 s, the values obtained before 1.5 s and after 4.0 s are not presented for clarity. Peak and mean power values applied to the COG of the system obtained from Methods 3 and 4 in the hang power clean were significantly different from the values obtained from Method 2 ($p<0.01$). Peak power values obtained from Methods 3 and 4 in weighted jump squat were significantly different from the value obtained from Method 2 ($p<0.05$). The mean power value obtained from Method 4 in weighted jump squat was significantly different from the value obtained from Method 2. In addition, the peak velocity of the COG of the system obtained from Method 2 is significantly lower than that of the barbell obtained from Methods 1, 3 and 4 in both exercises. Peak

Table 4.3 Peak velocity, peak force, peak power and mean power during hang power clean and weighted jump squat (mean ± SD). HPC = hang power clean, WJS = weighted jump squat, * significant difference from Method 1 ($p < 0.01$), † significant difference from Method 2 ($p < 0.05$), and ‡ significant difference from Method 2 ($p < 0.01$).

		Method 1	Method 2	Method 3	Method 4
HPC	Peak Velocity (m/s)	2.16 ± 0.25‡	1.48 ± 0.20*	2.16 ± 0.25‡	2.16 ± 0.25‡
	Peak Force (N)	1022 ± 171‡	2512 ± 310*	2358 ± 453*	2512 ± 310*
	Peak Power (W)	1644 ± 295‡	3076 ± 638*	3821 ± 917*‡	4017 ± 833*‡
	Mean Power (W)	795 ± 164‡	1325 ± 333*	1832 ± 414*‡	1804 ± 401*‡
WJS	Peak Velocity (m/s)	2.23 ± 0.16‡	1.99 ± 0.12*	2.23 ± 0.16‡	2.23 ± 0.16‡
	Peak Force (N)	718 ± 43‡	2151 ± 172*	2159 ± 231*	2151 ± 172*
	Peak Power (W)	1184 ± 115‡	3866 ± 451*	3567 ± 494*†	4427 ± 557*‡
	Mean Power (W)	675 ± 80‡	1936 ± 221*	2032 ± 341*	2324 ± 291*‡

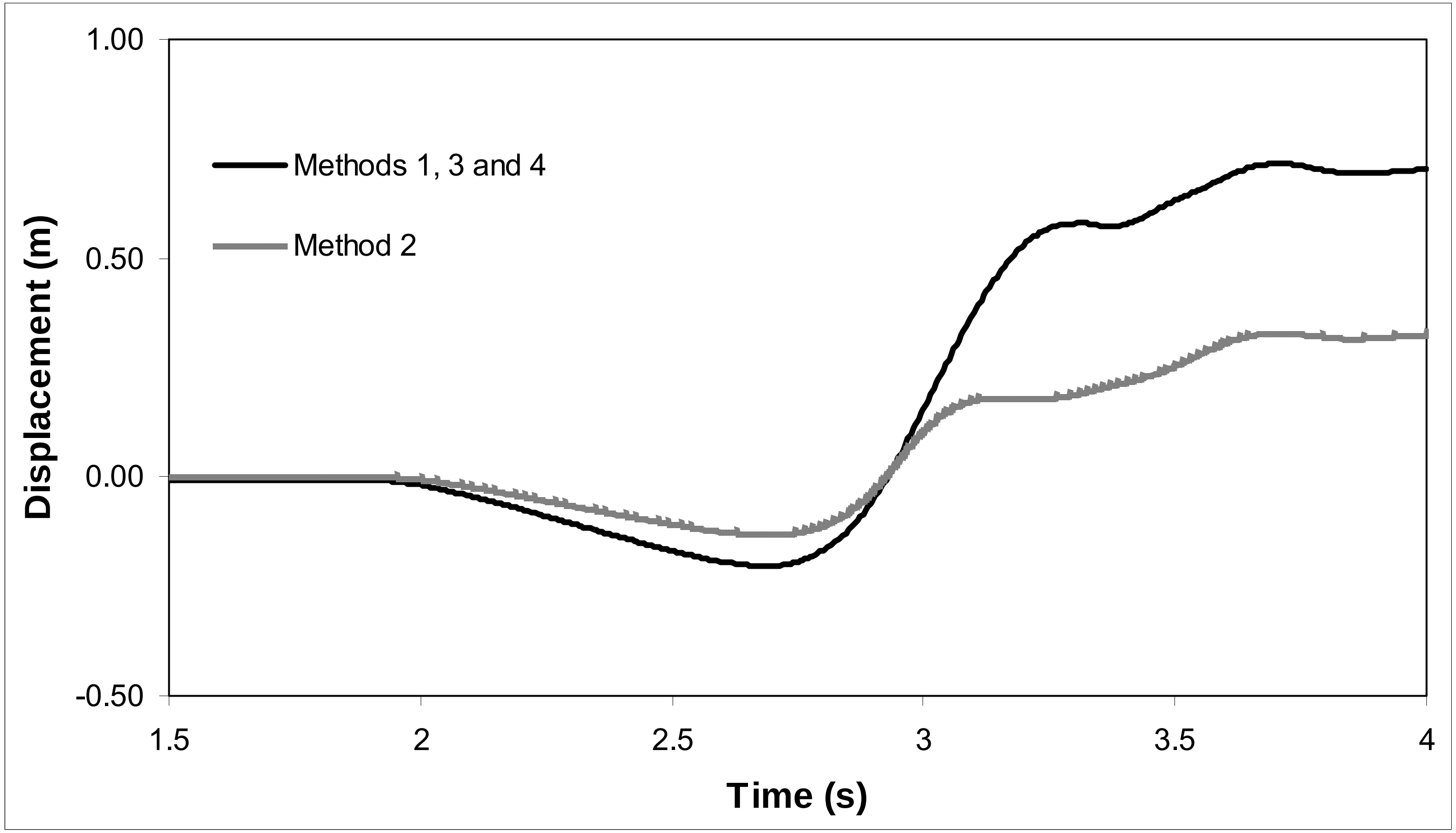

Figure 4.1 Displacement-time curve during hang power clean.

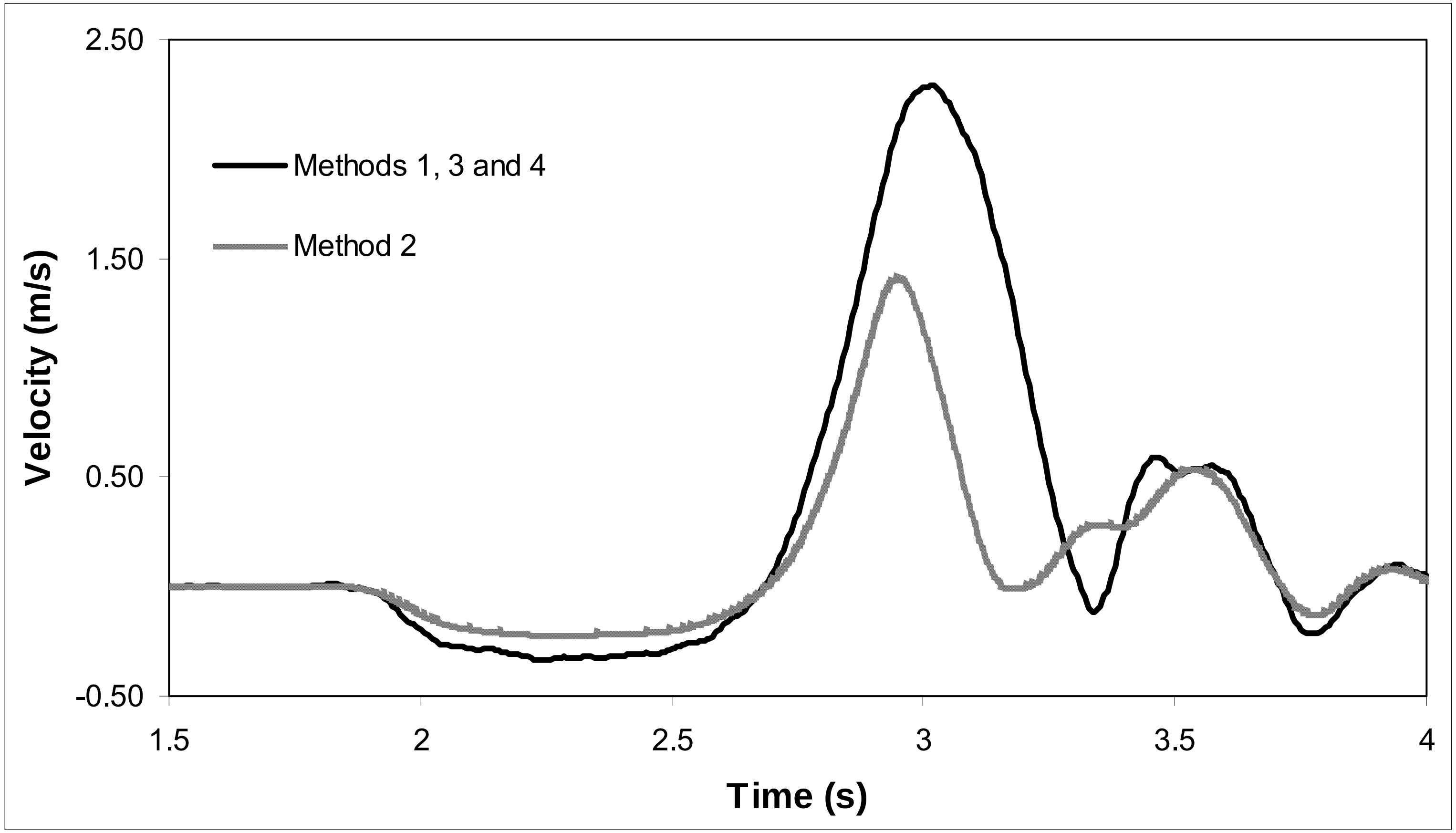

Figure 4.2 Velocity-time curve during hang power clean.

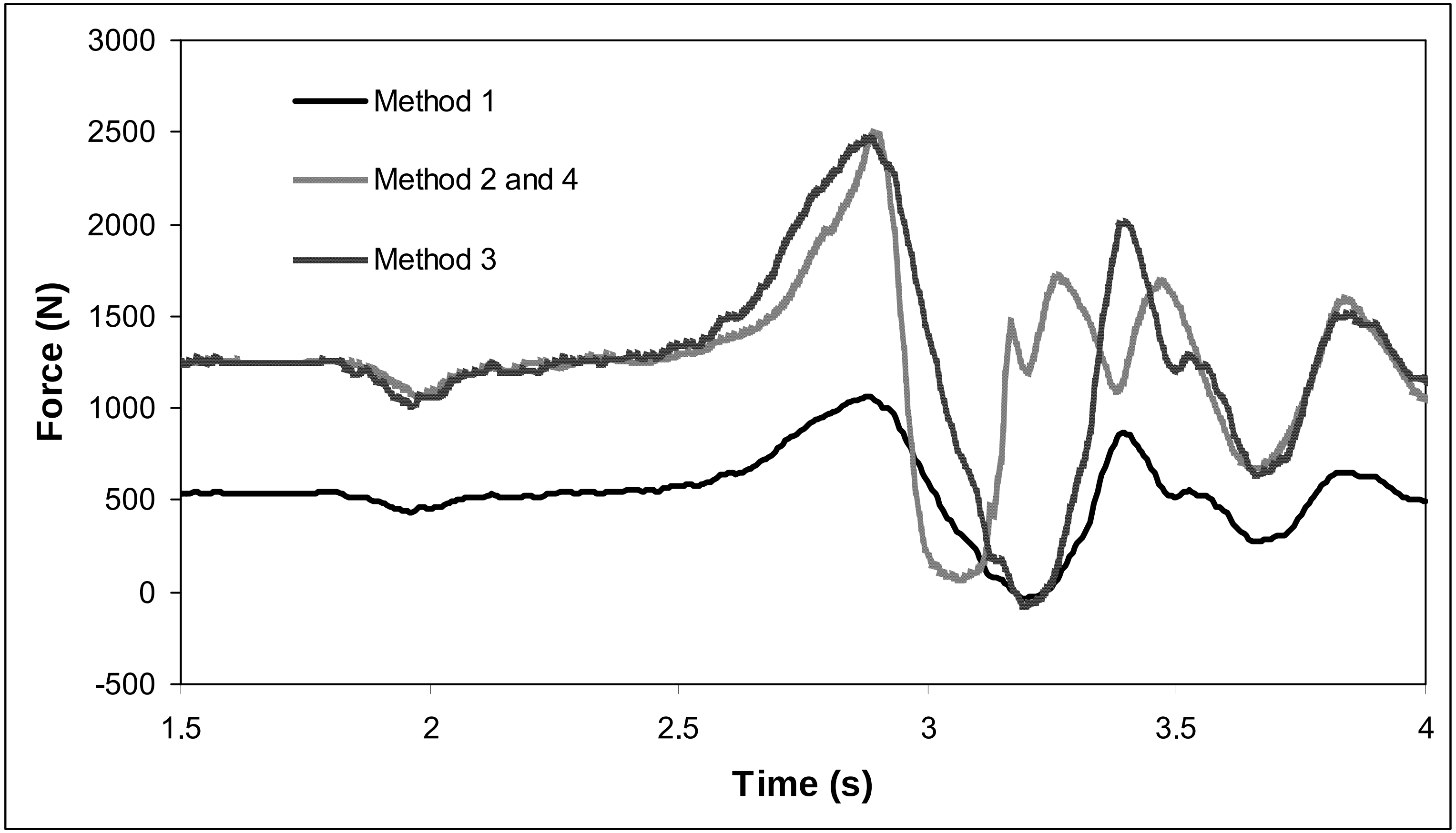

Figure 4.3 Force-time curve during hang power clean.

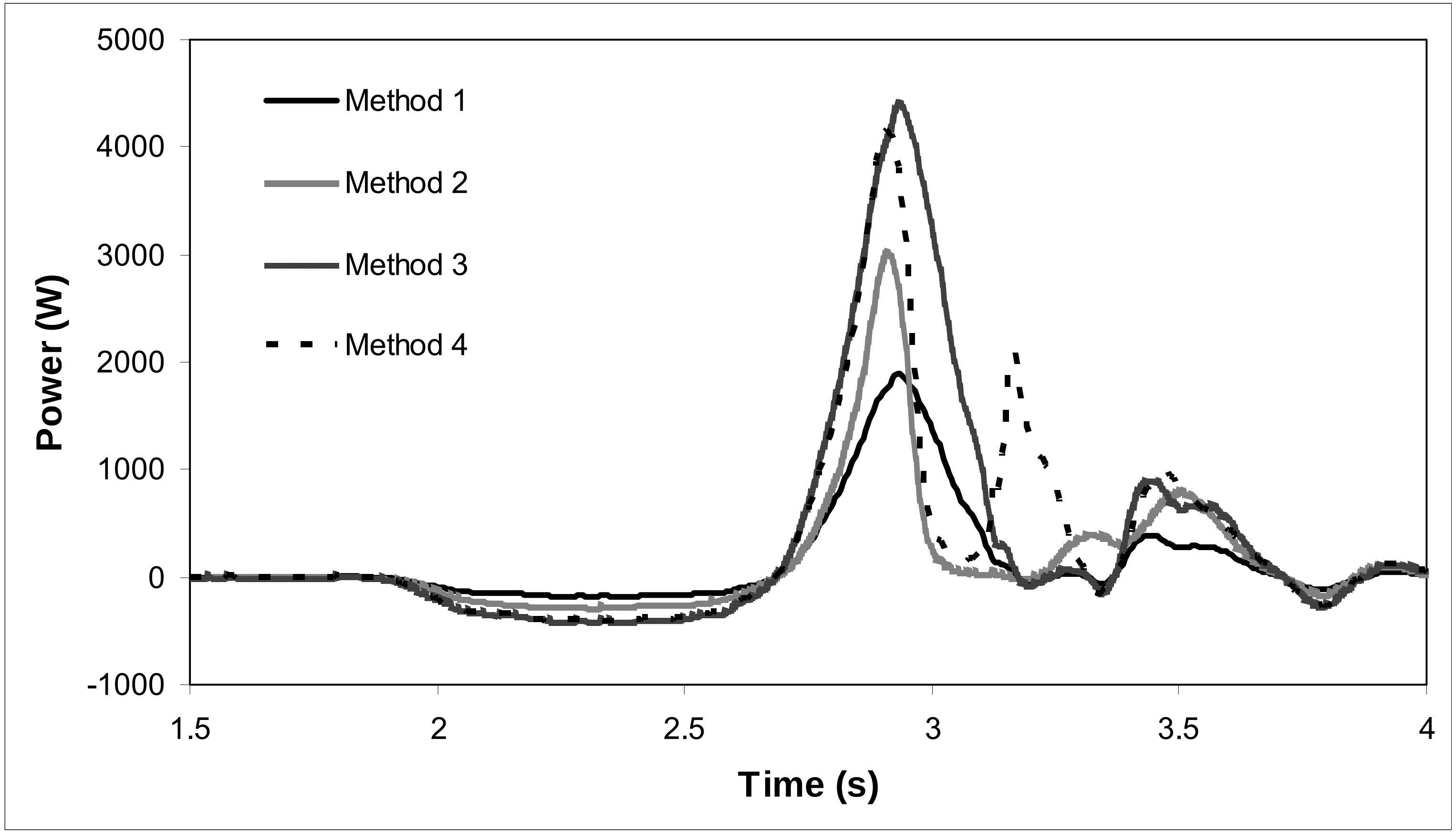

Figure 4.4 Power-time curve during hang power clean.

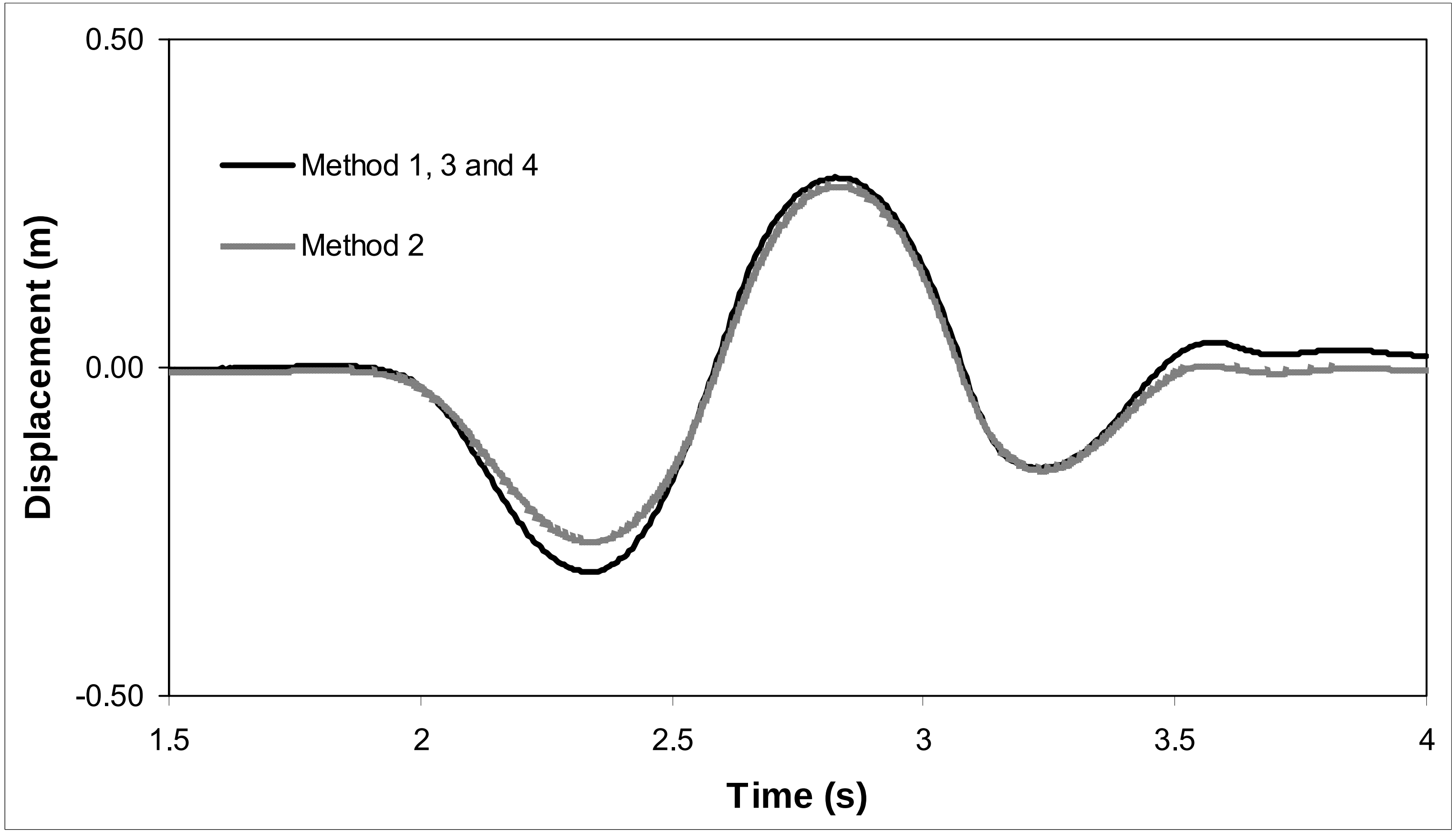

Figure 4.5 Displacement-time curve during weighted jump squat.

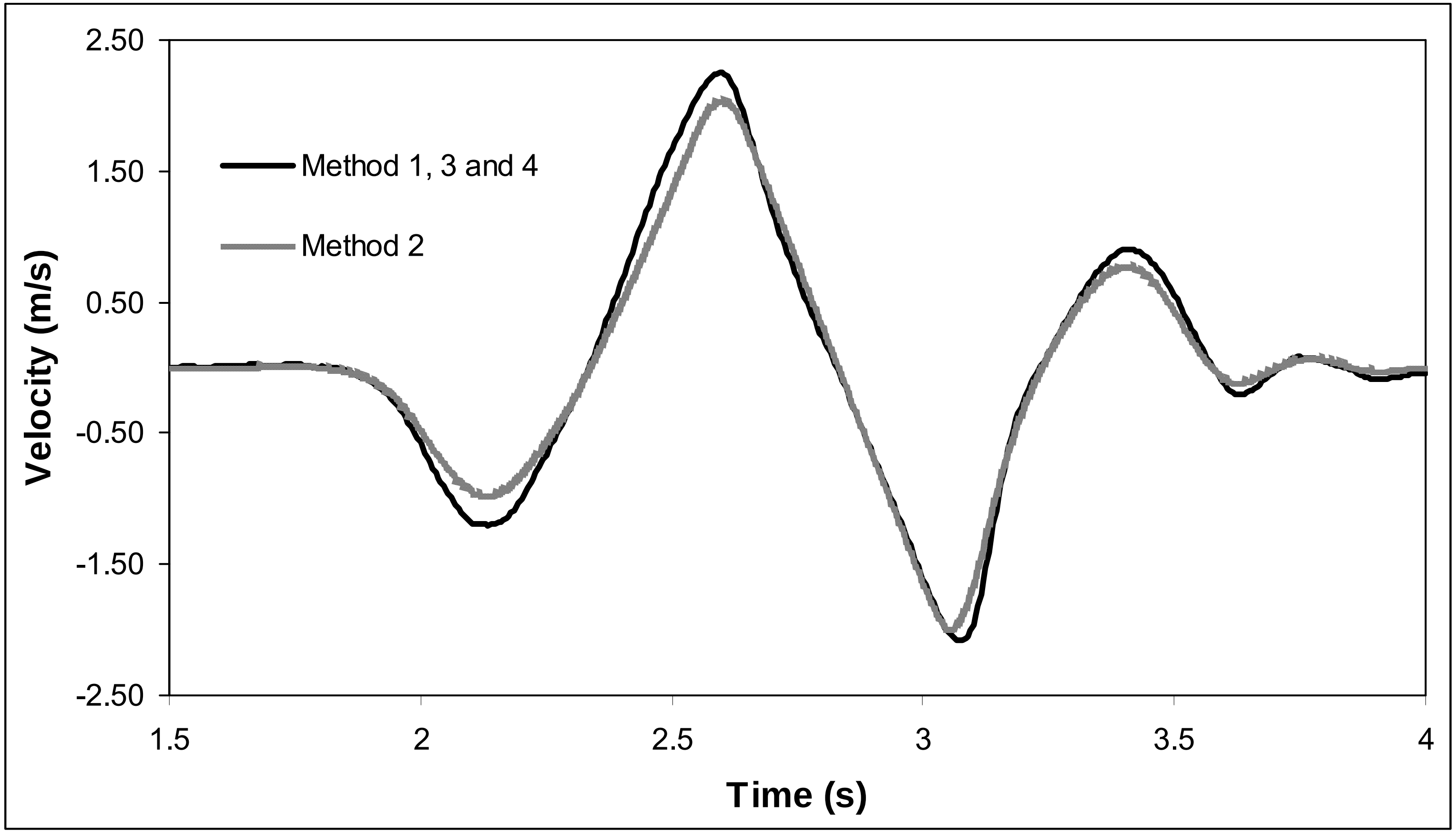

Figure 4.6 Velocity-time curve during weighted jump squat.

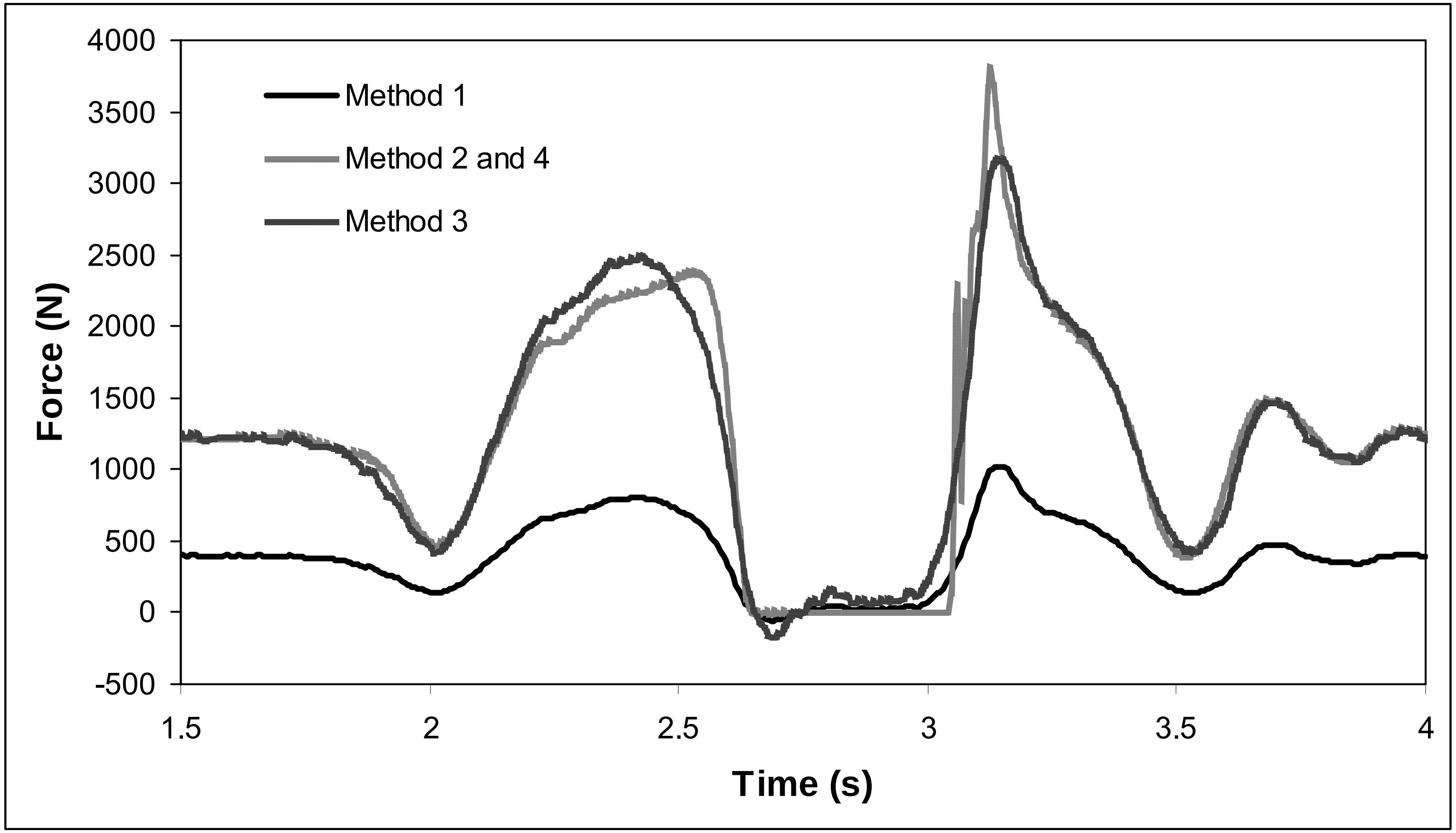

Figure 4.7 Force-time curve during weighted jump squat.

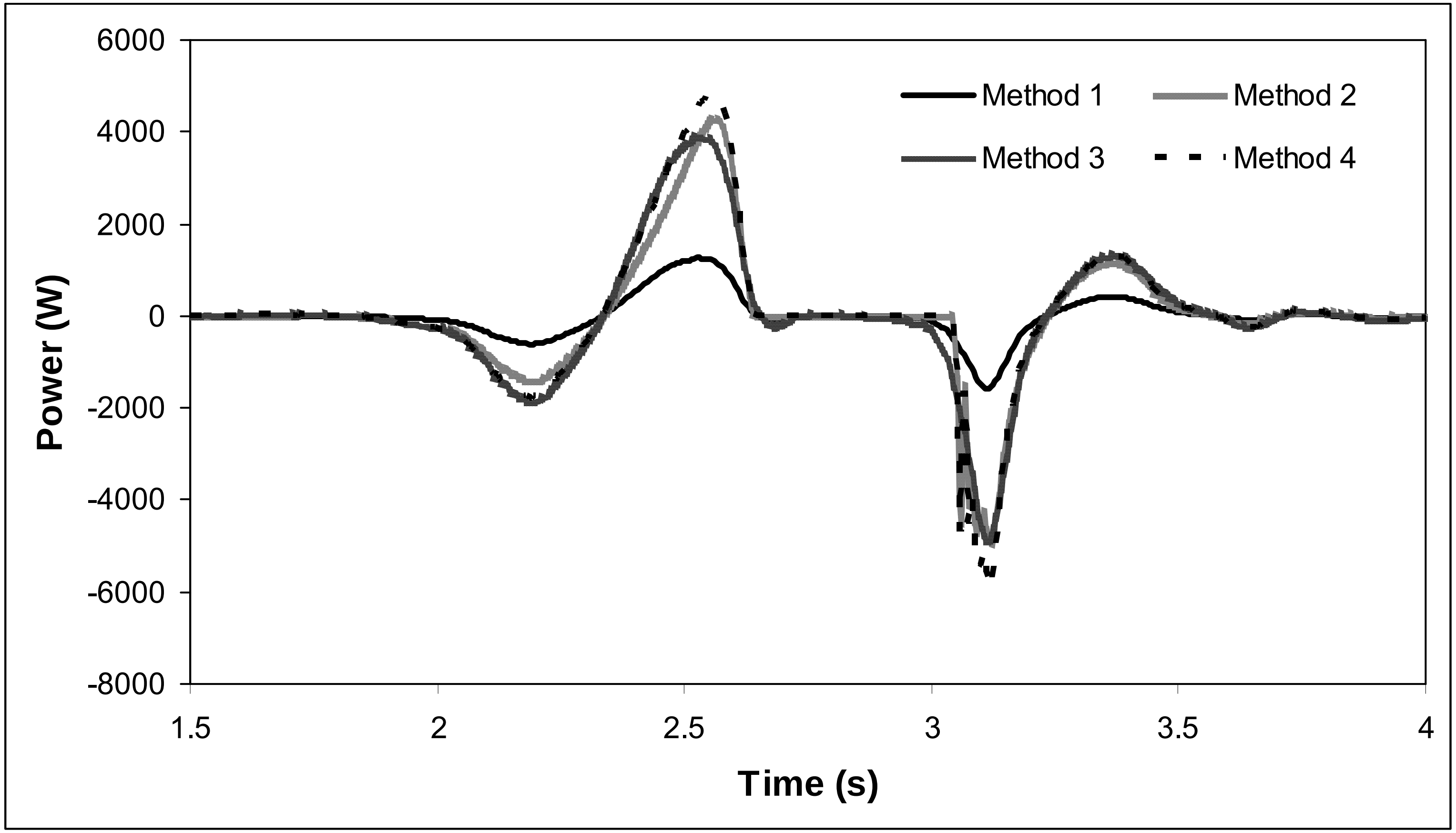

Figure 4.8 Power-time curve during weighted jump squat.

force, peak power, and mean power applied to the barbell obtained from Method 1 were significantly lower than the values applied to the system obtained from Methods 2, 3 and 4 in both exercises. There were significant correlations between the peak and mean power values obtained from Methods 1 and 2 in hang power clean and weighted jump squat (r = 0.65-0.81, p<0.01). The peak and mean power values were significantly correlated in all four methods (r = 0.80-0.93, p<0.01).

DISCUSSION

The major finding of this study was significant and meaningful differences in results for force, power and velocity depending on how these measures were derived. Further, Method 2 which involved measurement of all variables based only on GRF proved to be the most reliable technique (Tables 4.1 and 4.2). Theoretically, Method 2 is valid unless the exercise is started from the floor or pulling blocks because the force platform cannot measure forces applied remote to the plate surface (Hori et al., 2006). On the other hand, Methods 3 and 4 are valid only if the COG of the barbell moves in parallel with the COG of the system. The displacement and velocity of COG of the barbell and system during the weighted jump squat (Figures 4.5 and 4.6) were not as different as those curves of the hang power clean (Figures 4.1 and 4.2). However, the velocity of COG of barbell and that of system during the weighted jump squat were still significantly different, and the power outputs obtained from Methods 3 and 4 were different from that obtained from Method 2 (Table 4.8). Thus, we should not assume that the COG of the barbell and that of the system move exactly in parallel even during weighted jump squat. Because power is the product of force times velocity, the difference between the displacement-time curve (Figure 5), velocity-time curve (Figure 6) and force-time curve (Figure 7) obtained from different methods may be enlarged when force is multiplied by velocity. While several studies (Baker & Nance, 1999a; Stone et al., 2003a; Young et al., 2005) assumed that COG of barbell and that of system move in parallel during weighted jump squat, this appears to be an erroneous assumption as marked differences have been shown in the present study. On the other hand, the displacement of the COG of the barbell during the hang power clean was clearly larger than that of the system and this was even more evident for velocity (Figures 4.1 and 4.2). Since Hori et al. (2006) suggested that the COG of the barbell and that of the system did not move in parallel during weightlifting exercises, these results were expected in hang power clean.

The peak force, peak power, and mean power values applied to the barbell obtained from Method 1 were significantly lower than the values applied to the system obtained from Method 2 in both the hang power clean and the weighted jump squat as expected. This is because Method 1 only accounts for the forces applied to the barbell, and does not consider the acceleration or mass of the lifter's body. Thus, the differences between Methods 1 and 2 are expected when power is measured during the exercises that include large movement of the lifter's body such as hang power clean and weighted jump squat (Hori et al., 2006). Further, the less the relative weight of the barbell to body weight the greater disparity between measures of force and power. Although Method 1 exhibited lower power output values than Method 2, it does not mean Method 1 is incorrect. Rather, Method 1 is specifically measuring the power applied to the barbell which may be a primary outcome measure when assessing weightlifting performance. However, the correlations between power measured by Methods 1 and 2 suggests such barbell measures do not completely reflect the actual power output developed by the athlete and transmitted through the feet. As most sports involving jumping, sprinting and change of direction are dictated by power transfer through the lower extremities to the ground this is an important consideration in regards to validity of Method 1 for measuring sport relevant power performance.

It is noteworthy that the power value obtained from Method 2 (ICC = 0.89-0.97, CV = 1.8–7.9) exhibited higher ICC and smaller CV than that obtained from other methods (ICC = 0.58-0.94, CV = 2.5-15.4, Table 1 and 2). To explain this fact, two reasons are speculated. First, it seems that the subjects' power application toward the barbell was not as consistent as the power application toward the force platform. Although there was a significant correlation between the power applied to the barbell (Method 1) and that applied to the system (Method 2), it seems likely the ability to exert power toward the barbell is influenced by factors other than ability to exert power toward the ground. Second, to calculate force applied to the barbell in Method 1, the displacement-time data of the barbell was differentiated twice to obtain acceleration and thus force applied to the barbell or to the COG of the system and thus small errors are amplified resulting in reduced accuracy of force measurement. On the other hand, the GRF-time data was measured directly from the force plate and then integrated once to obtain velocity of the COG of the system in Method 2. Because Method 1 requires additional calculation, it may be possible that small measurement error occurring in

Table 4.4 Correlation between peak power values obtained from different methods. HPC = hang power clean, WJS = weighted jump squat, and ** correlation was significant at the 0.01 level.

		Method 1	Method 2	Method 3	Method 4
HPC	Method 1				
	Method 2	0.70**			
	Method 3	0.70**	0.74**		
	Method 4	0.72**	0.97**	0.81**	
WJS	Method 1				
	Method 2	0.74**			
	Method 3	0.69**	0.86**		
	Method 4	0.80**	0.98**	0.89**	

Table 4.5 Correlation between mean power values obtained from different methods. HPC = hang power clean, WJS = weighted jump squat, and ** correlation was significant at the 0.01 level.

		Method 1	Method 2	Method 3	Method 4
HPC	Method 1				
	Method 2	0.65**			
	Method 3	0..68**	0.63**		
	Method 4	0.63**	0.94**	0.67**	
WJS	Method 1				
	Method 2	0.81**			
	Method 3	0.79**	0.80**		
	Method 4	0.85**	0.98**	0.79**	

Table 4.6 Correlation between peak and mean power values obtained from different methods. HPC = hang power clean, WJS = weighted jump squat, and ** correlation was significant at the 0.01 level.

	Method 1	Method 2	Method 3	Method 4
HPC	0.87**	0.82**	0.90**	0.80**
WJS	0.90**	0.86**	0.93**	0.91**

displacement-time data of the barbell is magnified during the double differentiation process. This combined with the influence of data filtering and cut-off frequency can influence derived measures such as peak and mean power, a phenomenon well described in the biomechanics literature (Wood, 1982).

As was expected, there were very strong relationships between peak and mean power values (Table 4.8). Further, although mean power is believed more reliable than peak power (Hori et al., 2006), it was not the case in this present study (Table 4.1 and 4.2). In addition, it is suggested that peak power value is more related to the actual athletic performance (Dugan et al., 2004; Harman et al., 1991; Hori et al., 2006). Thus, scientists and practitioners should consider use of peak power values rather than mean. As mentioned previously, it is generally easier to find the peak power than to calculate the mean power, so that this finding would be useful.

In conclusion, the present study revealed the power output values applied to the COG of the system obtained from the barbell displacement-time data only (Method 3) and both the barbell displacement-time and the GRF-time data (Method 4) were significantly different from the value obtained from the GRF-time data only (Method 2). In addition, this study found significant correlation between the power applied to the barbell (Method 1) and that applied to the COG of the system (Method 2), as well as the strong correlation between peak and mean power values obtained from each method. It is speculated that the findings of this study might be applicable for female athletes, but the present study involved male subjects only. Thus, future research investigating the validity and reliability of these methods in female athletes is warranted.

PRACTICAL APPLICATIONS

Because of the difference between values obtained from the four methods, it is important to consider the results presented in previous studies using Methods 3 and 4 with caution (Baker & Nance, 1999a; Baker et al., 2001b; Chiu et al., 2003; Stone et al., 2003a; Winchester et al., 2005; Young et al., 2005). Practitioners are recommended to use displacement measurement and bar mass to estimate power output applied to a barbell, and measurement of GRF to measure power output applied to the COG of a system during hang power clean and weighted jump squat. Practitioners should also be aware of the fact that power output values calculated using these two methods are basically different quantities. Usually, it is the latter (i.e., power output applied to the COG of a system) that is of importance as the displacement of the COG of a subject's body accounts for a meaningful portion of mechanical work during exercises such as hang power clean and weighted jump squat (Chiu et al., 2004). Thus, the use of GRF data may be the most direct and valid way to measure power output during hang power clean and weighted jump squat. If practitioners use barbell displacement measurement as an alternative to GRF measurement, they should be aware of the limitations of this method. Although the values obtained from Methods 1 and 2 were significantly correlated (r = 0.65 – 0.81), measurement of barbell kinetics and kinematics may not adequately explain the effects of a training intervention on changes in whole body power capacity. In other words, the improvement of power output applied to the barbell may not necessarily be associated with the improvement of the power output of the total body applied the ground. For example, it may be that power applied to the barbell is improved due to the improvement of lifting technique even if the ability to exert force and power toward the ground is not improved.

CHAPTER 5

STUDY 3

DOES PERFORMANCE OF HANG POWER CLEAN DIFFERENTIATE PERFORMANCE OF JUMPING, SPRINTING, AND CHANGING OF DIRECTION?

Journal of Strength and Conditioning Research (In Press, April 2007)

Naruhiro Hori, Robert U. Newton, Warren A. Andrews, Naoki Kawamori,
Michael R. McGuigan and Kazunori Nosaka

INTRODUCTION

Performance of jumping, sprinting and changing of direction (COD) impacts considerably on success in team sports such as American football, Australian Rules football, volleyball, and basketball (Fry & Kraemer, 1991; Fry et al., 1991; Hoffman, 1996; Young et al., 2005). It has been well documented that power is one of the important factors in athletic performance (Baker & Nance, 1999a; Cronin & Sleivert, 2005; Cronin & Hansen, 2005; Newton & Kraemer, 1994; Young et al., 2005). Power is the mechanical quantity that expresses the rate of doing work (Enoka, 1994), and is largely dependant on the ability to exert the highest possible force (i.e. maximum strength) (Schmidtbleicher, 1992; Stone et al., 2003a; Stone et al., 2003b). Thus, how maximum strength and power are effectively developed are important issues for athletes and coaches in those sports. To optimise athletes' performance in competition, it is important to develop maximum strength during the early phase of long term training and transfer maximum strength to power effectively as the competition becomes closer (Harris et al., 2000; Plisk & Stone, 2003). There is an agreement among researchers and practitioners (Harris et al., 2000; Plisk & Stone, 2003; Wilson et al., 1993) that using training exercises involving heavy resistance such as the squat is an effective method to develop maximum strength. On the other hand, training exercises should involve rapid acceleration extended through the entire movement to develop power, and weightlifting exercises are commonly prescribed for this purpose (Hori et al., 2005).

Weightlifting exercises include two competition lifts in the sport of weightlifting (i.e. "snatch" and "clean and jerk") and variation of these exercises such as hang power clean. The weightlifting exercises involve exerting high forces against the ground and applying these forces rapidly, so that it appears an ideal form of exercise to exhibit high power output (Hori et al., 2005). For example, Garhammer (1993) reported that snatch, clean and jerk exhibit much higher power outputs compared to squat and deadlift. The movement of weightlifting exercises allows an athlete to accelerate the barbell through the entire range of pulling or driving movement, and does not require the athlete to decelerate the barbell velocity actively. Once the athlete completes the acceleration of the barbell, the barbell's upward movement is controlled by the influence of gravity (Hori et al., 2005). Because of these characteristics, it has been speculated that weightlifting exercises are beneficial to improve an athlete's capability of power production (Chiu & Schilling, 2005; Hori et al., 2005; Newton & Kraemer, 1994). As a result, many strength and conditioning programs incorporate weightlifting exercises for their athletes. For example, most of the strength and conditioning coaches in the National Football League (88%), National Basketball Association (95%), and National Hockey League (100%) in North America report having employed weightlifting exercises in their programs (Ebben & Blackard, 2001; Ebben et al., 2004; Simenz et al., 2005).

The purpose of this study was to investigate whether the athlete who has high performance in hang power clean has high performances in sprinting, jumping and COD. The hang power clean is a common weightlifting exercise among athletes, and the technique of this exercise is relatively easy to learn compared to other weightlifting exercises. This was the rationale for using the hang power clean in this study. If the athletes who have high performance in hang power clean has high performance in jumping, sprinting and COD, it could be speculated that the strength qualities required for high performance in such a weightlifting exercise are the same strength qualities critical for high performance in jumping, sprinting and COD. At present, scientific research to support the efficacy of the weightlifting exercises is scarce. While several studies (Canavan et al., 1996; Carlock et al., 2004; Garhammer & Gregor, 1992; Haff et al., 1997; Hoffman et al., 2004; Kawamori et al., 2005; Stone et al., 1980; Tricoli et al., 2005) have examined the relationships between the biomechanical characteristics of weightlifting exercises and jumping, there is limited information available about the relationships between the performance of weightlifting exercises, sprinting and COD (Baker & Nance, 1999a; Hoffman et al., 2004; Tricoli et al., 2005). It was envisaged that the findings of this investigation would help elucidate why the weightlifting exercises have been so popular. Second, the study would determine whether the weightlifting exercises share common strength qualities with jumping, sprinting and COD. Finally, the results would allow us to speculate on the efficacy of the HPC for developing maximum strength, power and performance of jumping, sprinting, and COD.

METHODS

Experimental Approach to the Problem

Twenty-nine semiprofessional Australian Rules football players participated in the present study. We tested seven measurements consisting of one repetition maximum (1RM) hang power clean to evaluate performance of weightlifting exercise, 1RM front squat to evaluate maximum strength, power output during the counter movement jump with 40 kg barbell (CMJ 40) and without external load (CMJ) to evaluate maximal power, jump height of CMJ to evaluate jump performance, 20 m sprint time to evaluate sprint performance, and 5-5 COD (Figure 1) time to evaluate COD performance. The subjects were then divided into two groups based on whether they were above or below the median score for 1RM hang power clean. Values obtained from all other tests were then compared between these two groups. In addition, correlations between measurements among all subjects were calculated to examine the strength of relationships.

Subjects

Twenty-nine male semi-professional Australian Rules football players were recruited. Their age, height, and body mass (mean ± SD) were, 21.3 ± 2.7 yr, 1.8 ± 0.1 m, and 83.6 ± 8.2 kg. The present study was conducted during January and February 2006. All subjects were familiar with basic resistance exercises such as bench press and back squat from their previous seasons. During their off season strength and conditioning program (October 2005 to January 2006), the subjects performed hang power clean and front squat 2-3 times per week under the supervision of their club's coaching staff. At the time of data collection, all subjects were able to perform hang power clean and front squat appropriately and none of them had any illness or injuries which would affect the test results. After the data collection of the present study, the subjects' strength and conditioning program moved to the specific preparation phase to prepare their 2006 season in which the first match was held in April 2006. This study was approved by Edith Cowan University Human Research Ethics Committee. All subjects read the information letter explaining the procedure of the study, and signed the informed consent document.

Tests and the Order

The testing was administered over three different days, and each test day was separated by at least 48 hours to minimize the effects of fatigue. Each test day consisted of the following measurements.

- Day 1: 20 m sprint and 5-5 COD
- Day 2: CMJ and CMJ 40
- Day 3: 1RM hang power clean and 1RM front squat

Before the start of each test day, subjects were instructed to warm-up with several minutes of aerobic exercises (jogging, biking or rowing) and dynamic stretching.

Test Procedure

One RM hang power clean: Hang power clean began from a position such that the subjects stood and held the barbell in front of his body. The subject started the movement by lowering the barbell to above his knee. From above the knee, the subject moved the barbell upward explosively, and received the barbell at his shoulder height (Kawamori et al., 2005). The investigator estimated subject's 1RM from his recent training log, and planned the weights to be lifted during a series of warm-up sets. In each set, the subject performed one to three repetitions, and the weight was increased every set. The subject started the warm-up with the set using bar only (20 kg), added 20-40 kg each set until the load was about 60% of estimated 1RM and then added 5-10 kg until the load was 90% of estimated 1RM. After these sets were completed, the weight was increased by 2.5 or 5 kg after each set until their 1RM was determined. The absolute value and the value divided by the subject's body mass were used for the statistical analysis.

One RM front squat: The subject's feet position and grip width were self selected. The subject placed the barbell on his anterior part of deltoid muscles and clavicles. Then, he squatted until his posterior surface of thigh became parallel to the floor, and stood up to his starting position. The movement was observed by the investigator to ensure test compliance. Prior to the test, the subject completed a few warm-up sets as explained in the 1RM hang power clean. The absolute value and the value divided by the subject's body mass were used for the statistical analysis.

Countermovement jump with 40 kg weight: The subject's feet position, barbell position and grip width were self selected. He squatted down to his comfortable depth, and then jumped vertically as high as possible. The CMJ 40 was performed on a force platform (Performance Plate, Fitness Technology, Adelaide, Australia) so as to record ground reaction force (Figure 5.1). Vertical component of ground reaction force (GRF) was sampled at 200 Hz for 5 s using the computer software (Ballistic Measurement System, Innervations, Perth, Australia), and the vertical component of peak power

Figure 5.1 Experimental set up for weighted jump squat with measurement of ground reaction force.

output was obtained using the following process; velocity of the center of gravity (COG) of the system was calculated from GRF-time data based on the relationship between impulse and momentum in which impulse is equal to the changes in momentum, and power applied to the COG of the system was calculated as the product of velocity of the COG of the system and GRF at each time point (Dugan et al., 2004; Hori et al., 2006). The subjects performed the CMJ 40 twice, and the Intra-class Correlation Coefficient (ICC) obtained from the two repetitions was 0.97. The higher peak power value of the two repetitions (absolute value and the value divided by the subject's body mass) was used for the statistical analysis.

Countermovement jump: Peak power during CMJ was also calculated using the force platform and computer software described above. In addition, the peak displacement (jump height) was estimated from changes in the velocity of the COG of the system. The subject squatted to his comfortable depth, and then without pausing, jumped as high as possible. The subject placed a light fiberglass stick on their shoulders, and kept holding the stick throughout the tests to eliminate the effects of arm swing and isolate force production by the lower extremities (Young et al., 2005). The subject performed the CMJ twice, and the ICC was obtained from the two repetitions (0.95 for peak power and 0.85 for jump height). The peak power value (absolute value and the value divided by the subjects' body mass) and jump height during the trial which exerted higher peak power value were used for statistical analysis.

20m sprint: 20m sprint performance was measured by using the two pairs of timing gates (Kinematic Measurement System, Fitness Technology, Adelaide, Australia). Timing gates were placed 0 m and 20 m from start line. Details of this equipment has been published elsewhere (Cronin & Hansen, 2005). The subject started in a standing position with the toes of the preferred foot just inside the starting line. The subject was instructed to start in his own time without any starting signal. Each subject performed the sprinting twice, and the better time was used for further statistical analysis. ICC obtained from the two repetitions was 0.80.

5-5 COD: Two lines (start line and 5m line) were marked on the ground, 5m apart (Figure 5.2). The pair of timing gates described above was placed at the start line. The subject sprinted from the start line, then turned 180° on a line 5 m distant, and sprinted until the subject passed the start line again. The subject started as described for the 20 m sprint. When he turned, he was asked to either step on, or step across the 5 m line. The time taken was obtained electronically from the timing gate system. This test was performed two times each with changing direction by right and left feet, and the best time of four trials (i.e. two of right foot and two of left foot) was used for statistical analysis. ICC obtained from the two best scores was 0.80.

Statistical Analyses

The subjects were divided into top half group (n = 14) and bottom half group (n = 14) based on 1RM hang power clean relative to the subject's body mass. The 1RM value relative to the subject's body mass was used because Baker and Nance (1999a) reported that the value relative to the body mass was more meaningful than the absolute value to examine the relationships between maximum strength, power and athletic performance. Since the present study had recruited an odd number of subjects, the middle of all 29 subjects was excluded from this statistical analysis (i.e. 1st to 14th subjects: top half group, 15th subject: excluded from this analysis, and 16th-29th subjects: bottom half group). The values obtained from each test were compared between these two groups using one-way analyses of variance. The independent variable was group, and dependent variables were 1RM hang power clean (absolute value and value relative to the subjects' body mass), 1RM front squat (absolute value and value relative to the subjects' body mass), peak power in CMJ 40kg and CMJ (absolute value and value relative to the subjects' body mass), jump height in CMJ (cm), time in 20m sprint (s), and time in 5-5 COD (s). In addition, correlations between all measurements among all subjects were calculated by Pearson's product moment correlation coefficient (n = 29). The criterion for statistical significance was set at $p \leq 0.05$ for all analyses.

RESULTS

The results for the different groups in the 1RM hang power clean relative to the subjects' body mass are shown in Table 5.1, and correlations between each measurement among all subjects are presented in Table 5.2. As can be observed from Table 5.1, the top half group exhibited significantly higher values than the bottom half group except for absolute peak power in CMJ and CMJ 40, and time in 5-5 COD. In addition, there were significant correlations found between most of, but not all combination of hang power clean performance and measurements of maximum strength, power and jump, sprint and COD performance (Table 5.2).

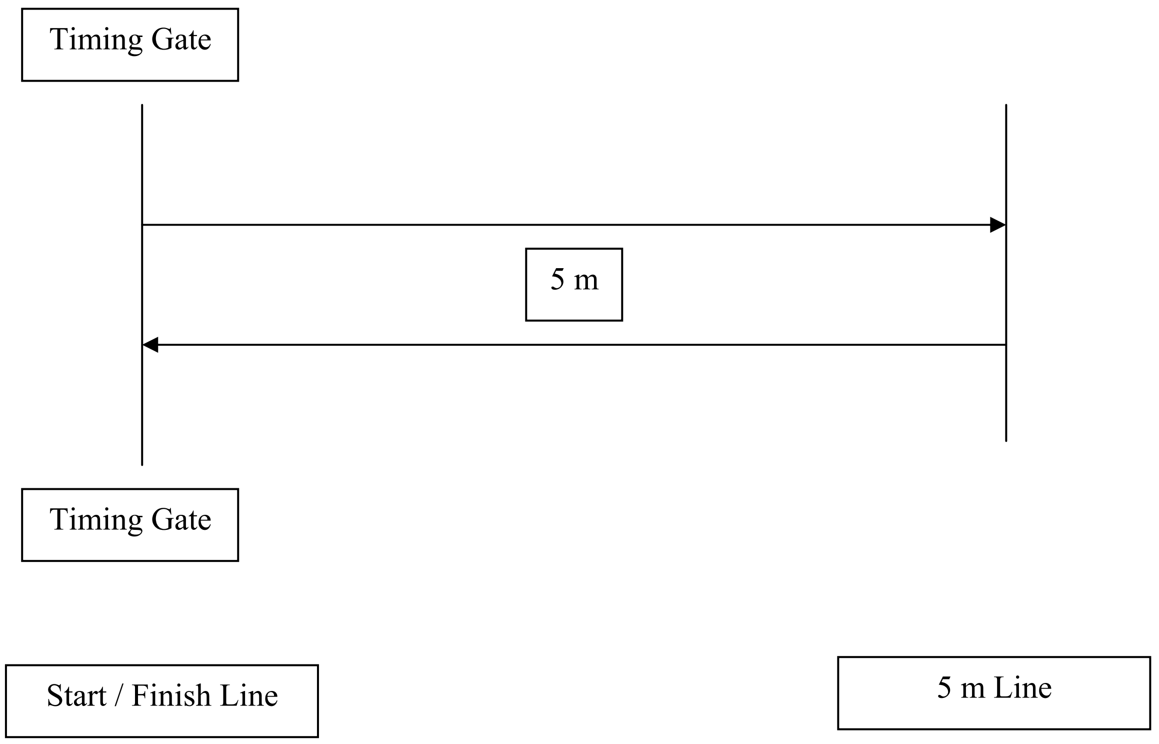

Figure 5.2 Description of 5-5 change of direction.

Table 5.1 Comparison between top 50% and bottom 50% in the 1RM hang power clean. HPC: hang power clean, PP: peak power, FS: front squat, CMJ: counter movement jump with 40 kg barbell, CMJ: counter movement jump without external load, *: $p < 0.05$, and **: $p < 0.01$.

	Top 50% (mean ± SD)	Bottom 50% (mean ± SD)
HPC 1RM **	80.2 ± 8.6	70.2 ± 5.9
HPC 1RM / BM **	1.0 ± 0.1	0.8 ± 0.1
FS 1RM *	105.4 ± 7.2	96.6 ± 13.7
FS 1RM / BM **	1.3 ± 0.1	1.1 ± 0.2
CMJ 40 kg PP (W)	3952 ± 522	3752 ± 375
CMJ 40 kg PP (W/kg)**	49.9 ± 4.8	43.8 ± 3.4
CMJ PP (W)	3910 ± 318	3984 ± 555
CMJ PP (W/kg)**	50.3 ± 4.9	45.0 ± 3.1
CMJ height (cm)*	43.1 ± 4.1	39.9 ± 3.2
Sprint (s)**	3.11 ± 0.04	3.22 ± 0.09
COD (s)	2.58 ± 0.09	2.65 ± 0.11

Table 5.2 Relationships between each measurement (Pearson's r). HPC: hang power clean, / BM: relative to body mass, FS: front squat, CMJ 40: counter movement jump with 40 kg barbell, PP: peak power, CMJ: counter movement jump without the external load, *: $p < 0.05$, and **: $p < 0.01$.

	HPC 1RM	HPC 1RM / BM	FS 1RM	FS 1RM / BM	CMJ 40 PP	CMJ 40 PP / BM	CMJ PP	CMJ PP / BM	CMJ Height	Sprint	COD
HPC 1RM											
HPC 1RM / BM	0.68**										
FS 1RM	0.39*	0.25									
FS 1RM / BM	0.08	0.55**	0.70**								
CMJ 40 PP	0.58**	0.13	0.32**	-0.11							
CMJ 40 PP / BM	0.38*	0.60**	0.26	0.45*	0.63**						
CMJ PP	0.21	0.13	-0.15	-0.21	-0.01	-0.09					
CMJ PP / BM	0.30	0.58**	0.11	0.38	0.50**	0.92**	-0.26				
CMJ height	0.41*	0.51**	0.29	0.34	0.54**	0.75**	-0.12	0.81**			
Sprint	-0.58**	-0.57**	-0.60**	-0.51**	-0.49**	-0.62**	0.19	-0.58**	-0.69**		
COD	-0.41*	-0.34	-0.51**	-037*	-0.39*	-0.38*	-0.13	-0.27	-0.42*	0.52**	

DISCUSSION

In this study, we attempted to reveal whether athletes who possess higher performance in hang power clean perform better in jumping, sprinting and COD than athletes with lower performance in this exercise. To gain a better understanding, we also examined if there were any underlying strength qualities that were common to the hang power clean and jumping, sprinting and COD. The major outcome was that the top half group in the 1RM hang power clean relative to the subjects' body mass had higher performance of jumping and sprinting, and demonstrated higher maximum strength measured by the 1RM front squat (both absolute and relative to the subject's body mass) and higher power measured by peak power output in the CMJ 40 (relative to the subject's body mass) and CMJ (relative to the subject's body mass). Thus, it seems that the individual who can perform well in the 1RM hang power clean possesses high maximum strength and power that is essential for peak performance of jumping and sprinting. One RM hang power clean relative to the subject's body mass, 1RM front squat relative to the subject's body mass, power output relative to the subject's body mass in CMJ 40 and CMJ, jump height in CMJ, and time in the 20 m sprint were significantly correlated each other ($r = 0.51 – 0.60$). From these significant correlations, it seems reasonable to assume that the 1RM hang power clean was sharing similar strength qualities required for jumping and sprinting. Previous studies (Sleivert & Taingahue, 2004; Weyand et al., 2000) have reported the ability to apply high force and power in the vertical direction is related to performance of sprinting, so that it has been suggested that the activity exerting high force and power rapidly in vertical direction such as the weightlifting exercises would help to develop sprint performance (Baker & Nance, 1999a; Young et al., 2001a). Also, the present study is in agreement with the previous studies (Carlock et al., 2004; Stone et al., 1980) reporting that the subject who can exhibit higher 1RM in the weightlifting exercises was able to jump higher and exert higher power output during vertical jump movement.

However, there was no significant difference in performance of 5-5 COD between the groups. Interestingly, there was no significant correlation between the 5-5 COD time and the 1RM hang power clean relative to the subject's body mass ($r = -0.34$), but there was a significant correlation between the 5-5 COD time and the absolute value of 1RM hang power clean ($r = -0.41$). It was hypothesized that the value relative to the subject's body mass would be more related to the 5-5 COD performance than the absolute value (Baker & Nance, 1999a), and we cannot propose any explanation of this unexpected result. In our opinion, the 5-5 COD can be divided into two phases; a) start line to 5 m line, and b) 5 m line to start line. The ability to accelerate quickly at the start line is an important part of 5-5 COD. However, when the athlete changes his direction, the higher the velocity before the COD, the higher is the momentum that he needs to overcome. Perhaps it is counterproductive if the athlete accelerates his velocity more than necessary prior to the COD. Therefore, it is speculated that the optimal decision making about how much the athlete accelerates his velocity and when he starts to decelerate during the first 5 m is the other factor determining the performance of 5-5 COD. The 1RM front squat (both absolute and body mass relative) and CMJ 40 power (both absolute and body weight relative) were significantly correlated with 5-5 COD (r = 0.37 – 0.51), so that maximum strength and power are still factors contributing the performance of 5-5 COD. However, it appears likely that other factors influence COD performance such as the ability of optimal decision making. Possibly, it may be the reason why the present study did not show any significant difference between 5-5 COD time in the two groups. Further, the importance of the ability to accelerate/decelerate his velocity in performance of COD may be varied dependent on the pattern of running such as distance of sprint and angle of COD (Little & Williams, 2005; Young et al., 2002; Young et al., 2001b).

While the present study found that the performance of 1RM hang power clean could differentiate performance of jumping and sprinting, the design used in the present study could not explain the cause and effect. For practitioners, it is important to consider if the training of weightlifting exercises (e.g. hang power clean) would improve the performance of jumping, sprinting and COD. At present, only three training studies (Hoffman et al., 2004; Stone et al., 1980; Tricoli et al., 2005) have investigated the effects of training with weightlifting exercises on the performance of jumping, sprinting and/or COD. Stone et al. (1980) reported that 14 weeks training with weightlifting exercises improved jump performance significantly. However, this study did not examine the effects of weightlifting exercises on sprinting and COD performance. Hoffman et al. (2004) compared the effects of 15 weeks of weightlifting exercises versus powerlifting exercises (i.e. squat, bench press, and deadlift) on jumping, sprinting and COD performance, and reported the efficacy of weightlifting exercises on jumping performance. However, this study had limitations in their measurements of performance. For example, the pre-test values of sprint and COD were taken during pre-season of the previous year which was several months prior to when the training intervention started. In this manner, the effects of weightlifting exercises on sprint and COD might not have been assessed appropriately. Tricoli et al. (2005) have reported that the improvement in jumping and sprinting performance was larger for a weightlifting group compared with a vertical jump training group after an 8-week training intervention performed three times a week. However, the study used physical education students as subjects who had no lower-body strength training for three months prior to the investigation. Therefore, it is questionable if the findings from this study can be applied to athletes, particularly those who already have an extensive resistance training background. As a future direction, it is warranted further investigation involving well controlled training interventions overcome the weakness of previous training studies (Hoffman et al., 2004; Stone et al., 1980; Tricoli et al., 2005).

In conclusion, the present study found that the group possessing the higher 1RM hang power clean relative to the body mass also possessed higher maximum strength, power and performance of jumping and sprinting. However, the 1RM hang power clean relative to the subject's body mass could not differentiate the good and poor performance of COD. There were significant correlations between the 1RM hang power clean relative to the subject's body mass, maximum strength, power and performance of jumping and sprinting, but there was no correlation between the 1RM hang power clean relative to the subject's body mass and COD although there were significant correlations between absolute value and the performance of COD.

PRACTICAL APPLICATIONS

From the results of this study, it may be speculated that the training of the weightlifting exercises such as the hang power clean may be effective to improve the athlete's capability of power, and subsequently athletic performance which requires high power for skills such as jumping, sprinting. However, there was no significant difference between the 5-5 COD time of top and bottom half groups in the 1RM hang power clean relative to the subject's body mass, and the correlation coefficient between the 1RM hang power clean (both absolute and relative to body mass) and jumping, sprinting and COD (r = 0.37 – 0.58) implied that there was a large amount of variance which the 1RM hang power clean could not explain. From the findings of the present study, practitioners may incorporate the weightlifting exercises into their programs, but it is also recommended to take a holistic approach to improve jump, sprint and COD performance which includes skill practice in addition to development of maximum strength and power.

In addition to the finding discussed above, the present study also suggests that 1RM hang power clean may be a good benchmark test of strength and power. In general, practitioners cannot conduct the performance measurement test as frequently as they want because of a number of uncontrollable reasons. For example, sport teams located in cold environments cannot conduct sprint performance tests outdoors during the winter. Further, unless sufficient testing equipment (e.g. force plate, jump and reach, or timing gates) are available, it is very difficult to test large numbers of athletes at once. Thus, practitioners often encounter problems of scheduling especially during the in-season. Practitioners working in these circumstances may consider the 1RM hang power clean as a convenient way to assess the athletes' neuromuscular performance instead of actual measurement of jumping height or sprinting time since the hang power clean can be performed as a part of regular training. Particularly when the training program is in high intensity and low volume phase, typically used in-season, experienced practitioners could easily estimate their athletes' 1RM even if their 1RM were not actually measured. The hang power clean appears to provide a useful summary measure to track athlete strength and power for monitoring progression and training program effectiveness as well as possible declines due to injury, illness or overtraining.

CHAPTER 6

STUDY 4

COMPARISON OF WEIGHTED JUMP SQUAT TRAINING WITH AND WITHOUT ECCENTRIC BRAKING

Journal of Strength and Conditioning Research (In Press, September 2007)

Naruhiro Hori, Robert U. Newton, Naoki Kawamori, Michael R. McGuigan,
Warren A. Andrews, Dale W. Chapman and Kazunori Nosaka

INTRODUCTION

To maximize power output during a given resistance-training exercise, it is recommended that an object (i.e. a barbell and/or an athlete's body) be projected into the air so that undesirable deceleration is minimized (Newton et al., 1996). For this reason, weighted jump squat has attracted considerable attention among scientists and practitioners (McBride et al., 2002; McEvoy & Newton, 1998; Newton et al., 1999; Wilson et al., 1993). During weighted jump squat, an athlete places a barbell on the shoulders or holds dumbbells in the hands, lowers to a comfortable depth (typically about 90˚ of knee flexion), and then jumps vertically for maximum height (propulsive phase) after which the athlete's body and the weight (barbell or dumbbells) accelerates downward under the influence of gravity until the athlete contacts the ground again and initiates the landing phase. During the landing phase, an athlete is exposed to a considerable magnitude of ground reaction force (GRF) particularly the landing impact at initial contact which can be quantified as the impulse over the first 50ms (Humphries et al., 1995). Humphries et al. (1995) reported that the peak GRF at landing phase was 3.04 times body weight (BW) while the peak force during propulsive phase was 2.19 BW during weighted jump squat with 10 kg load.

During the landing phase of the weighted jump squat, muscle groups of the lower extremities work eccentrically (Hoffman et al., 2005). It has been well documented that unaccustomed eccentric muscle actions cause greater muscle damage than concentric muscle actions (Dierking & Bemben, 1998; Szymanski, 2001). Thus, it is speculated that the eccentric muscle action during the landing phase of weighted jump squat causes considerable muscle damage in athletes unaccustomed to such exercise (Hoffman et al., 2005). Further, there are some unsubstantiated claims that landing impact may cause injuries to the athlete such as cartilage degeneration, stress fractures, and tendinitis (Humphries et al., 1995; Ricard & Veatch, 1990). To minimize impact force at the initial contact during weighted jump squat, previous studies investigating the effects of weighted jump squat training have used various braking mechanisms to control the momentum on landing and thus the impulse that must be applied to decelerate (McBride et al., 2002; McEvoy & Newton, 1998; Newton et al., 1999; Wilson et al., 1993). For example, Humphries et al. (1995) reported that an electromagnetic braking mechanism reduced the peak impact force at landing by 155%. In their study (Humphries et al., 1995), the braking mechanism was activated only as the barbell descended, but it was not active during upward movement of the barbell in the propulsive phase.

However, any negative effects of reducing eccentric load and/or positive effects of exposure to landing impact have not been investigated fully in previous studies. Because a braking mechanism modifies the eccentric phase, a natural stretch shortening cycle is not experienced. This may reduce the training stimulus, and therefore reduce the magnitude of neuromuscular adaptations. Eccentric muscle action during the landing phase may cause positive adaptations. Several studies (Brandenburg & Docherty, 2002; Doan et al., 2002; Hortobagyi et al., 2001; Kaminski et al., 1998; Moore & Schilling, 2005) have reported that training emphasizing eccentric actions improves strength more than that of concentric actions only. Thus, once the athletes adapt to the exercise, the landing impact of the weighted jump squat may improve their strength without causing excessive muscle damage. If this eccentric muscle action initiates a positive adaptation, it is possible that weighted jump squats without a braking mechanism may be more beneficial than that with a braking mechanism. Therefore, the purpose of this study was to compare the effects of weighted jump squat training with and without a braking mechanism designed to reduce the eccentric load on strength, power and athletic performance under well controlled conditions.

METHODS

Experimental Approach to the Problem

An overview of the timeline of this study is presented in Figure 6.1. Twenty physically active male subjects were equally divided into two groups, Non-Braking Group (NBG) and Braking Group (BG). There were two phases to this research, the first being a training intervention comparing neuromuscular adaptations to weighted jump squat training with braking versus without braking. The second phase was an investigation of the GRF kinetics of weighted jump squat with and without braking to investigate possible mechanisms for any differential training effects.

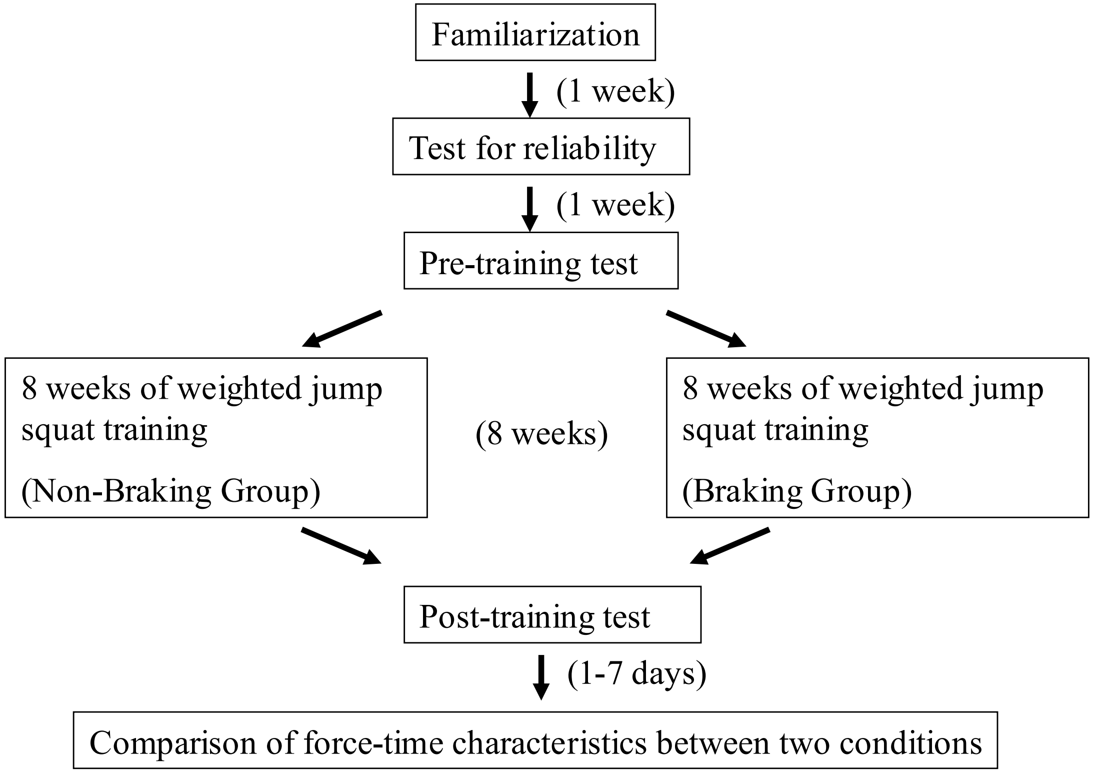

Figure 6.1 Time line for testing and training of Non-Braking and Braking Groups.

All subjects participated in a training program consisting of weighted jump squats twice a week for 8 weeks. Subjects in NBG performed weighted jump squat without a braking mechanism while subjects in BG performed weighted jump squat with a braking mechanism designed to produce an upward force during the descent phase. Strength, power and athletic performance were measured pre- and post-training intervention. To familiarize subjects with the test measurements, subjects completed a familiarization session two weeks prior to the pre-training test. All subjects participated in a separate testing session at the completion of the training intervention to assess the kinetics of the two conditions. This phase of the study was completed at the end so that all subjects were very familiar with the weighted jump squat protocol and equipment.

Subjects

Twenty male subjects were recruited by advertising flyer and announcement in university lectures and tutorials. All subjects were regularly participating in some form of physical activity such as weight training, running, swimming, cycling, and/or ball games (e.g. soccer) two to three times per week on average, but were not competitive athletes. A subject inclusion criterion was that they had no injury or medical condition which would limit their training adaptation or place them at risk of injuries. To standardize initial strength level, the subjects were eliminated if their one repetition maximum (1RM) half squat (testing protocol for 1RM half squat explained shortly) was less than their body mass at the pre-training test. This criterion of strength level was chosen based on our previous study (Wilson et al., 1993). The subjects height, body mass and sum of seven skinfolds (i.e. triceps, subscapular, biceps, supraspinale, abdominal, front thigh, and medial calf) are presented in Table 6.1 (Norton et al., 2000). These subjects were equally divided into two groups based on their 1RM half squat value pre-training intervention. Prior to the training intervention, independent sample t-tests did not reveal any significant differences in descriptive characteristics or dependent variables between the groups except for their age. As shown in Table 1, age in BG was significantly higher than that of NBG ($p < 0.01$). Since the pre-training strength was considered the most important matching variable, grouping was based on 1RM half squat and the 1.1 years difference in age between groups acknowledged. This study was approved by the University's Human Research Ethics Committee. All subjects read an information letter explaining the procedure of the study, and signed an informed consent document.

Table 6.1 Descriptive subject data (Mean ± S.D.). **: Significant difference ($p < 0.01$).

	Non-Braking Group (n = 10)	Braking Group (n = 10)
Age (yr)	23.7 ± 2.1	24.8 ± 5.0 **
Height (cm)	179.0 ± 5.0	177.3 ± 6.0
Body mass (kg)	81.1 ± 7.8	76.4 ± 7.0
skinfolds (mm)	91.3 ± 24.5	87.7 ± 34.8

Training Intervention

Subjects in both groups participated in training sessions consisting of weighted jump squat, 6 sets of 6 repetitions at 30% of 1RM half squat at pre-training test twice a week for 8 weeks. Throughout the 8-week training intervention, subjects were asked to maintain their lifestyle, and not alter their volume or intensity of physical activity in particular. No subjects reported any acute/chronic injuries during the training intervention. McBride et al. (2002) compared the effects of weighted jump squat training using 30 vs. 80% of 1RM loads, and reported that the 30% loading was more effective than 80% to improve athletic performance. This has been used as the rationale for a 30% of 1RM load to be applied in the present study. The length of the training intervention was chosen based on previous studies (McBride et al., 2002; Newton et al., 1999). In the weighted jump squat, subjects squatted down to a self selected depth of approximately 90° of knee flexion, and jumped immediately as high as possible. Subjects performed 6 repetitions of weighted jump squat without any pause between repetitions. Subjects took at least 1 minute rest between sets, but they were allowed to take as much rest as they needed. The cable end of the electromagnetic braking mechanism (Ballistic Braking System, Fitness Technology, Adelaide, Australia) was attached to the middle of barbell. Although the braking mechanism was attached for both groups during the weighted jump squat movement for consistency of training environment, the braking mechanism was active only during the downward movement for BG. The reduction of eccentric load for subjects in BG was controlled to be equal to the barbell weight. For example, if a subject in BG used a 50-kg barbell, the reduction of downward force was 490.5 N (mass × gravity). In all testing and training sessions, subjects rode on a stationary bike for 5 minutes at 100W intensity and 60 rpm for warm up.

Measurement of Strength, Power and Athletic Performance

Pre- and post-training tests were completed over 2 days, and administered in the following order; Day 1: Countermovement jump (CMJ), squat jump (SJ), drop jump, jump and reach, and 1RM half squat, and Day 2: Weighted jump squat, and isometric and isokinetic unilateral knee extension and flexion.

Counter movement jump and squat jump: Subjects were tested on two different types of jump; CMJ and SJ. In the CMJ, the subjects stood erect first, then squatted to a self selected depth of approximately 90˚ of knee flexion, and jumped immediately as high as possible without pausing. In the SJ, subjects were instructed to squat to a self selected depth of approximately 90˚ of knee flexion, pause 3 s in this position, and then jump as high as possible. During these jump movements, the subjects kept their hands on hips. The jumps were performed on a force platform (Quattro Jump – Type 9290AD, Kistler, Switzerland) and vertical GRF was sampled at a rate of 500 Hz for 10 s using dedicated hardware and software (Ballistic Measurement System, Innervations, Australia). Vertical velocity of the center of mass of the system (subject’s body and the barbell) was calculated from vertical GRF-time data using forward dynamics approach (Dugan et al., 2004; Hori et al., 2006). Peak power output in a vertical component was calculated as the product of vertical GRF and vertical velocity of the center of mass of the system (Dugan et al., 2004; Hori et al., 2006). This test was performed twice, and the highest peak power value was used for statistical analysis. In statistical analyses, both absolute value and value relative to body mass were used.

Drop jump: The force platform (Quattro Jump – Type 9290AD, Kistler, Switzerland) was used to measure the subject’s performance during the drop jump. The subjects were asked to step off a 40-cm box and jump immediately after the landing, aiming to produce the maximum height while minimizing ground contact time. During this jump movement, the subjects’ hands were kept on their hips. The force-time data from the force platform system were used to measure flight and contact time. Flight time was divided by contact time to determine the reactive strength index (RSI) (Newton & Dugan, 2002). The subjects performed drop jump twice, and the highest RSI value was used for statistical analysis.

Jump and reach: Jump and reach test was included as a representative measurement of athletic performance since this test involves more natural movement compared to the CMJ and SJ (Klavora, 2000). The test was administered by using a yard stick (Yard Stick II, Swift Performance Equipment, Australia). First, the standing reach height was established by having the subjects stand flat footed and reach up to displace the markers of the yard stick using the subjects' preferred hand. Then, the subjects were asked to jump as high as possible by using countermovement and arm swing, and displace the markers of the yard stick. The jump height was obtained as the reach height subtracted from the height of the marker that the subject displaced. The subjects were allowed to repeat the jump and reach test until the subject achieved his maximal height (typically less than 5 times) and the highest jump height was used for statistical analysis.

1RM half squat: The subjects performed two types of half squat; half squat concentric only (1RM Sq Con) and from eccentric to concentric (1RM Sq Ecc-Con). Subjects were tested for 1RM Sq Con first, then the 1RM Sq Ecc-Con second. Between these tests, subjects rested for at least 5 minutes. At the start of 1RM Sq Con, the barbell was placed on the safety bar of the power rack at the height of the bottom position of half squat (90° of knee flexion), and the subjects stood up from this position. In 1RM Sq Ecc-Con, barbell was placed on a power rack at approximately 10 cm below the subjects' shoulder height at the beginning of the test. The subjects positioned themselves under the barbell, stood up, stepped a few steps back, squatted down (90° knee flexion) and stood up. The subjects' feet position and grip width were self selected. Subjects placed the barbell on their upper trapezius muscles immediately below C7. From the subjects' familiarization sessions, the investigator estimated the subject's 1RM. The subjects started the warm up with sets of 1-5 repetitions with the bar only (20 kg), added weight of 20-40 kg each set until the load became about 60% of estimated 1RM, then added 5-10 kg until the load was 90% of estimated 1RM. After these sets were completed, the weight was increased by 2.5 or 5 kg each set until their 1RM was determined. Subjects were allowed to take as much rest as they needed between sets to minimize the effects of fatigue. The heaviest weight that the subjects successfully lifted was determined as their 1RM. The value of 1RM Sq Ecc-Con at pre-training test was used to determine the load of weighted jump squat for their training. In statistical analyses, both absolute value and value relative to body mass were used.

Weighted jump squat: Subjects performed weighted jump squat with 30% of 1RM Sq Ecc-Con obtained at each test. In the weighted jump squat, subjects squatted down to a self selected depth of approximately 90˚ of knee flexion, and jumped immediately as high as possible. The loads for this test were chosen to match the training protocol. The braking mechanism (Ballistic Braking System, Fitness Technology, SA, Australia) was not attached to the barbell during this measurement. The subjects' feet position, barbell position and grip width were the same as described at 1RM Sq Con and 1RM Sq Ecc-Con. Peak power output during the propulsive phase was obtained as described for CMJ and SJ. This test was performed twice, and the highest power output value was used for statistical analyses. In statistical analyses, both absolute value and value relative to body mass were used.

Isometric and isokinetic knee extension and flexion: The subject was positioned on an isokinetic dynamometer (Biodex, System 3 Pro & MVP Model #830 210, Shirley, NY). Subjects' movements were restricted using torso, pelvic, thigh and shin straps, and they held the handles to stabilize themselves. Seat position was set so that the subjects' hip joint angle was 95˚. Torque during isometric knee extension and flexion were measured in the following order: knee angle (full extension = 0˚) at 90, 70, 50, 30 and 10˚ (at each position, extension was followed by flexion). Only the left leg was tested due to constraints of time and to avoid subject test fatigue. At each position, subjects produced a 3-s sub-maximal effort, and two 3-s maximal efforts with a 30-s rest between repetitions. During the maximal effort set, the subjects were instructed to push the immovable shin pad as hard as possible. The highest peak torque value at each position was used for statistical analysis. For isokinetic knee extension and flexion, the subjects were tested in the following order of angular velocity; 60, 180, 300˚/s (concentric action) and -60˚ /s (eccentric action). Subjects performed one sub-maximal set of 3 repetitions for warm-up and one set of 3 repetitions with maximal effort at each angular velocity with 60-s rest between sets. During the maximal effort sets, the subjects were instructed to push the shin pad as hard and as rapidly as possible through the entire range of motion. The highest peak torque at each angular velocity was used for statistical analysis.

Comparison of Force-Time Characteristics between Two Conditions

All subjects performed weighted jump squat in Braking and Non-Braking Conditions on the force platform (Quattro Jump – Type 9290AD, Kistler, Switzerland). The subjects warmed up by riding a stationary bike for 5 minutes, and then performed weighted jump squat for 2 sets of 6 repetitions with maximum effort at the same load as used in the training intervention in each condition. The order of the two conditions was randomized. Prior to the maximum effort set, subjects completed several warm-up sets to adequately familiarize themselves with each different condition. Vertical GRF during maximum effort sets was sampled at a rate of 500 Hz for 15 s. Foot contact time, mean force, impulse and impulse for the first 50 ms in 2nd to 6th jump of 2 maximum effort sets (10 foot contacts per subject) in each condition were averaged. While the 1st jump started from a static standing position, the 2nd to 6th jumps were performed consecutively immediately after landing from the previous repetition, thus the 1st jump was different from 2nd to 6th jumps. That is the rationale why the 2nd to 6th jumps were analyzed, but not the 1st jump. Impulse was calculated as the product of mean force and foot contact time. Impulse for first 50 ms has been considered as a measurement of the risk of injuries due to the landing impact (Humphries et al., 1995; Ricard & Veatch, 1990), and that is why we included this measurement.

Statistical Analyses

To examine the reliability of test measurements, subjects (n = 20) were tested twice for all measurements a week before the pre-training tests, and intra-crass correlation coefficients (ICC) and coefficients of variance (CV) were calculated (Table 6.2). To compare the effects of two different training interventions, group (NBG and BG) × time (pre- and post-training) interactions were examined by using a repeated measures two-way analysis of variance (ANOVA) for all dependent valuables (n = 10 in each group). Paired samples t-tests were used to examine time effects pre- to post-training intervention within each group (n = 10) as well as for the two groups pooled (n = 20). In addition, paired samples t-tests were used to compare the force-time characteristics, such as foot contact time, mean force, impulse and impulse for first 50ms for the Braking versus Non-Braking conditions (n = 20 since all subjects in both groups were tested). Criterion for significance was set at $p \leq 0.05$ for all analyses.

Table 6.2 Intra-class correlation coefficients and coefficients of variation of measurements. CMJ: countermovement jump, SJ: squat jump, DJ: drop jump, J&R: jump and reach, Sq Con: 1RM squat concentric only, Sq Ecc-Con: 1RM squat eccentric to concentric, WJS: weighted jump squat, IQ: Isometric quadriceps strength, IH: Isometric hamstring strength, CQ: concentric quadriceps strength, CH: concentric hamstring strength, EQ: eccentric quadriceps strength, and EH: eccentric hamstring strength.

Measurements	ICC	CV	Measurements	ICC	CV
CMJ	0.97	2.2	IQ 30°	0.76	8.1
SJ	0.95	3.6	IH 30°	0.92	6.9
DJ	0.41	8.8	IQ 10°	0.71	8.4
J&R	0.97	2.3	IH 10°	0.84	9.0
Sq Con	0.98	3.9	CQ 60°	0.84	6.0
Sq Ecc-Con	0.97	4.6	CH 60°	0.86	4.8
WJS	0.97	2.7	CQ 180°	0.83	6.4
IQ 90°	0.88	7.1	CH 180°	0.78	8.6
IH 90°	0.89	6.3	CQ 300°	0.86	6.0
IQ 70°	0.93	4.9	CH 300°	0.89	6.4
IH 70°	0.89	6.7	EH 60°	0.92	5.2
IQ 50°	0.87	6.4	EQ 60°	0.84	7.6
IH 50°	0.94	6.0			

RESULTS

The majority of performance measures in jump tests (jump and reach, CMJ, SJ, weighted jump squat and drop jump) and squat tests (1RM Sq Con and Sq Ecc-Con) exhibited significant improvement from pre- to post-intervention for both BG and NBG as well as for all subjects pooled together (Tables 6.3, 6.4, 6.5 and 6.6). However, very few of the isometric/isokinetic knee extension/flexion measurements exhibited any significant time effects.

Table 6.3 Jump tests (Mean ± S.D.). *: significant difference from pre ($p < 0.05$), **: significant difference from pre ($p < 0.01$), †: significant interaction ($p < 0.05$), NB: Non-Braking Group, B: Braking Group, CMJ: countermovement jump, SJ: squat jump, WJS: weighted jump squat, DJ: drop jump, and J&R: jump and reach. % changes are obtained as (post value – pre value) / pre value × 100.

	Group	Pre	Post	% Change
CMJ (W)	NBG	4330 ± 705	4427 ± 711	2.2
	BG	4063 ± 619	4258 ± 588 *	4.8
	Pooled	4196 ± 660	4342 ± 641 *	3.5
CMJ Relative (W/kg)	NBG	53.4 ± 6.9	54.7 ± 8.0	2.4
	BG	53.2 ± 6.8	55.9 ± 7.0 *	5.1
	Pooled	53.3 ± 6.6	55.3 ± 7.3 *	3.8
SJ (W)	NBG	3876 ± 806	4149 ± 775 **	7.0
	BG	3660 ± 803	4067 ± 673 **	11.1
	Pooled	3768 ± 790	4108 ± 708 **	9.0
SJ Relative (W/kg)	NBG	47.6 ± 8.0	51.1 ± 7.7 **	7.4
	BG	48.0 ± 9.6	53.5 ± 8.9 **	11.5
	Pooled	47.8 ± 8.6	52.3 ± 8.2 **	9.4
WJS (W)	NBG	3974 ± 737	4128 ± 616	3.9
	BG	3660 ± 612	4090 ± 575 **	11.7
	Pooled	3817 ± 679	4109 ± 580 **	7.6
WJS Relative (W/kg) †	NBG	49.1 ± 8.6	50.9 ± 6.2	3.7
	BG	47.9 ± 6.9	53.7 ± 7.3 **	12.1
	Pooled	48.5 ± 7.6	52.3 ± 6.7 **	7.8
DJ	NBG	1.94 ± 0.25	2.06 ± 0.45	6.2
	BG	1.95 ± 0.33	2.13 ± 0.36	9.2
	Pooled	1.94 ± 0.29	2.09 ± 0.40 *	7.7
J&R (cm)	NBG	51.4 ± 7.6	54.2 ± 7.6 **	5.4
	BG	53.2 ± 8.9	55.9 ± 8.0 **	5.1
	Pooled	52.3 ± 8.1	55.1 ± 7.6 **	5.4

Table 6.4 Squat tests (Mean ± S.D.). *: significant difference from pre ($p < 0.05$), **: significant difference from pre ($p < 0.01$), NB: Non-Braking Group, B: Braking Group, Sq Con: 1RM squat concentric only, and Sq Ecc-Con: 1RM squat eccentric to concentric. % changes are obtained as (post value – pre value) / pre value × 100.

	Group	Pre	Post	% Change
Sq Con (kg)	NBG	119.0 ± 34.6	127.3 ± 39.3 *	7.0
	BG	125.5 ± 26.4	141.3 ± 25.8 **	12.6
	Pooled	122.3 ± 30.1	134.3 ± 33.1 **	9.8
Sq Con Relative	NBG	1.5 ± 0.4	1.6 ± 0.5 *	6.7
	BG	1.7 ± 0.3	1.9 ± 0.4 **	11.8
	Pooled	1.6 ± 0.4	1.7 ± 0.4 **	6.2
Sq Ecc-Con (kg)	NBG	119.8 ± 30.8	126.0 ± 27.5 *	5.2
	BG	121.5 ± 27.0	132.8 ± 21.3 **	9.3
	Pooled	120.6 ± 28.2	129.4 ± 24.2 **	7.3
Sq Ecc-Con Relative	NBG	1.5 ± 0.4	1.6 ± 0.3 *	6.7
	BG	1.6 ± 0.4	1.8 ± 0.3 **	12.5
	Pooled	1.5 ± 0.4	1.7 ± 0.3 **	13.3

There was a significant interaction between groups for three variables: peak power relative to body mass during weighted jump squat (Figure 6.2), peak torque during isometric knee extension at 10˚ (Figure 6.3) and peak torque during isokinetic concentric knee flexion at 300˚ /s (Figure 6.4) indicating a differential effect of the training stimuli.

Comparing the landing kinetics for the Non-Braking versus Braking conditions, there was no difference between foot contact time of the two conditions. However, mean force, impulse and impulse for first 50 ms in Non-Braking condition were significantly higher than Braking condition (Table 6.7). Typical examples of force-time curves during a foot contact in each condition (i.e. with and without eccentric braking) obtained from a representative subject are presented in Figure 6.5.

Table 6.5 Isometric strength tests (Mean ± S.D.). *: significant difference from pre ($p < 0.05$), **: significant difference from pre ($p < 0.01$), †: significant interaction ($p < 0.05$), NB: Non-Braking Group, B: Braking Group, IQ: Isometric quadriceps strength, and IH: Isometric hamstring strength. % changes are obtained as (post value – pre value) / pre value × 100.

	Group	Pre	Post	% Change
IQ 90° (Nm)	NBG	249.1 ± 48.7	242.5 ± 48.4	-2.6
	BG	221.2 ± 43.6	231.0 ± 41.0	4.4
	Pooled	235.1 ± 47.2	236.8 ± 44.0	0.7
IH 90° (Nm)	NBG	89.6 ± 24.5	99.3 ± 28.4	10.8
	BG	90.2 ± 22.4	97.2 ± 22.2	7.8
	Pooled	89.9 ± 22.9	98.3 ± 24.8	9.3
IQ 70° (Nm)	NBG	266.8 ± 64.6	261.2 ± 68.4	-2.1
	BG	232.6 ± 42.5	236.5 ± 48.4	1.7
	Pooled	249.7 ± 56.0	248.9 ± 59.0	-0.3
IH 70° (Nm)	NBG	105.2 ± 29.2	105.8 ± 22.5	0.6
	BG	100.2 ± 27.0	103.9 ± 25.7	3.7
	Pooled	102.7 ± 27.5	104.9 ± 23.5	2.1
IQ 50° (Nm)	NBG	216.5 ± 48.4	202.1 ± 54.6	-6.7
	BG	192.7 ± 34.8	192.1 ± 32.0	-0.3
	Pooled	204.6 ± 42.8	197.1 ± 43.9	-3.7
IH 50° (Nm)	NBG	115.5 ± 32.7	116.1 ± 30.1	0.5
	BG	107.4 ± 30.2	115.2 ± 33.9	7.3
	Pooled	111.4 ± 30.9	115.6 ± 31.2	3.8
IQ 30° (Nm)	NBG	149.0 ± 28.3	141.5 ± 30.0	-5.0
	BG	138.7 ± 24.4	139.6 ± 22.3	0.6
	Pooled	143.9 ± 26.3	140.5 ± 25.7	-2.4
IH 30° (Nm)	NBG	122.9 ± 32.2	121.7 ± 30.4	-1.0
	BG	118.3 ± 29.3	122.5 ± 30.1	3.6
	Pooled	120.6 ± 30.0	122.1 ± 29.4	1.2
IQ 10° (Nm) †	NBG	85.0 ± 16.6	81.8 ± 15.6	-3.8
	BG	70.0 ± 10.4	77.2 ± 12.9 *	10.3
	Pooled	77.5 ± 15.6	79.5 ± 14.2	2.6
IH 10° (Nm)	NBG	122.5 ± 33.4	125.1 ± 28.1	2.1
	BG	118.6 ± 24.3	124.1 ± 28.3 *	4.6
	Pooled	120.5 ± 28.5	124.6 ± 27.4	3.4

Table 6.6 Isokinetic strength tests (Mean ± S.D.). *: significant difference from pre ($p < 0.05$), **: significant difference from pre ($p < 0.01$), †: significant interaction ($p < 0.05$), NB: Non-Braking Group, B: Braking Group, CQ: concentric quadriceps strength, CH: concentric hamstring strength, EQ: eccentric quadriceps strength, and EH: eccentric hamstring strength. % changes are obtained as (post value – pre value) / pre value × 100.

	Group	Pre	Post	% Change
CQ 60°/s (Nm)	NBG	201.4 ± 37.4	196.1 ± 36.8	-2.6
	BG	187.1 ± 33.8	188.7 ± 38.9	0.9
	Pooled	194.3 ± 35.5	192.4 ± 37.0	-1.0
CH 60°/s (Nm)	NBG	126.8 ± 25.8	128.1 ± 17.9	1.0
	BG	124.0 ± 21.9	128.8 ± 25.1	3.9
	Pooled	125.4 ± 23.4	128.4 ± 21.2	2.4
CQ 180°/s (Nm)	NBG	149.9 ± 26.0	153.1 ± 21.8	2.1
	BG	147.0 ± 31.9	149.6 ± 36.2	1.8
	Pooled	148.4 ± 28.4	151.3 ± 29.1	2.0
CH 180°/s (Nm)	NBG	112.8 ± 27.4	115.9 ± 15.5	2.7
	BG	101.9 ± 20.4	112.1 ± 19.8 **	10.0
	Pooled	107.3 ± 24.1	114.0 ± 17.4 *	6.2
CQ 300°/s (Nm)	NBG	126.3 ± 22.0	133.4 ± 23.2	5.6
	BG	128.3 ± 27.0	126.3 ± 36.2	-1.6
	Pooled	127.3 ± 24.0	129.8 ± 29.8	2.0
CH 300°/s (Nm) †	NBG	124.0 ± 22.6	134.1 ± 18.4 **	8.1
	BG	118.5 ± 32.7	113.2 ± 26.7	-4.5
	Pooled	121.2 ± 27.5	123.6 ± 24.8	2.0
EH 60°/s (Nm)	NBG	152.8 ± 35.7	159.6 ± 23.0	4.5
	BG	134.6 ± 24.9	142.2 ± 35.2	5.6
	Pooled	143.7 ± 31.4	150.9 ± 30.3	5.0
EQ 60°/s (Nm)	NBG	230.1 ± 62.9	229.0 ± 59.9	-0.5
	BG	209.6 ± 52.8	233.2 ± 75.2	11.3
	Pooled	219.8 ± 57.5	231.1 ± 66.2	5.1

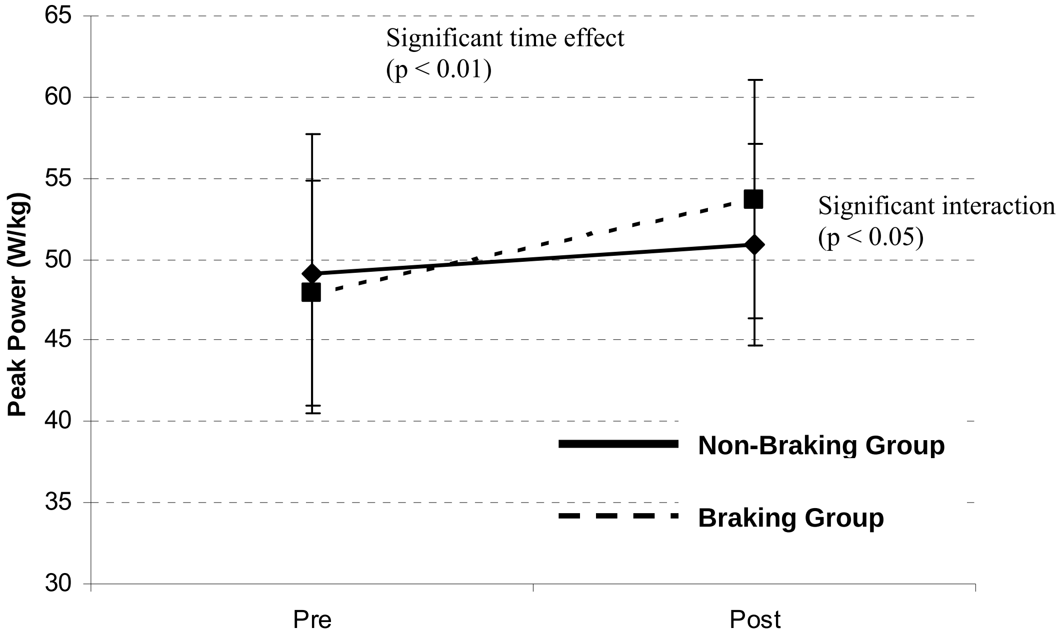

Figure 6.2 Peak power relative to body mass during weighted jump squat.

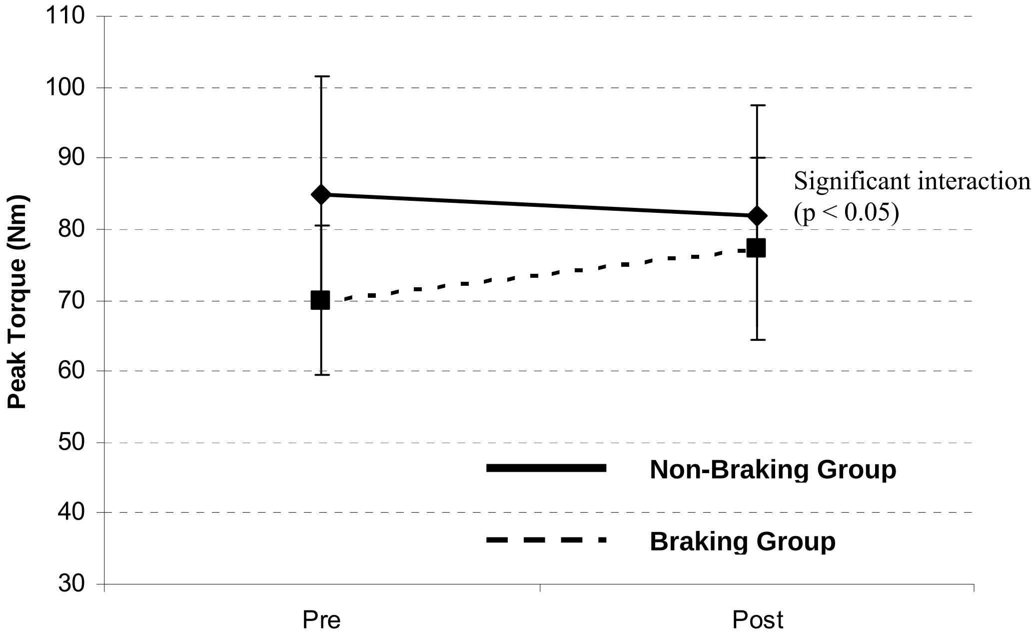

Figure 6.3 Peak torque during isometric knee extension at 10°.

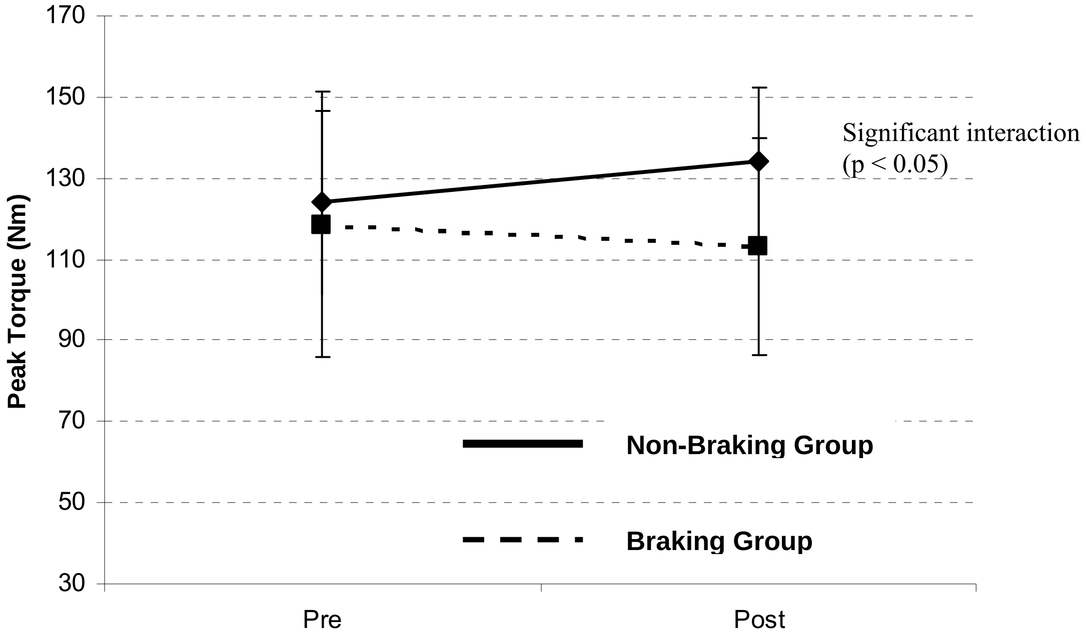

Figure 6.4 Peak torque during isokinetic concentric knee flexion at 300°/s.

Table 6.7 Foot contact time, mean force and impulse. **: Significant difference ($p < 0.01$). % differences are obtained as (Non-Braking condition – Braking condition) / Non-Braking condition × 100.

	Non-Braking Condition	Braking Condition	% Differences
Foot Contact Time (s)	0.79 ± 0.10	0.81 ± 0.11	2.5
Mean Force (N) **	1660 ± 247	1494 ± 188	-10.0
Impulse (Ns)**	1301 ± 165	1196 ± 165	-8.1
Impulse for first 50 ms (Ns)**	35.6 ± 8.5	23.2 ± 6.4	-34.8

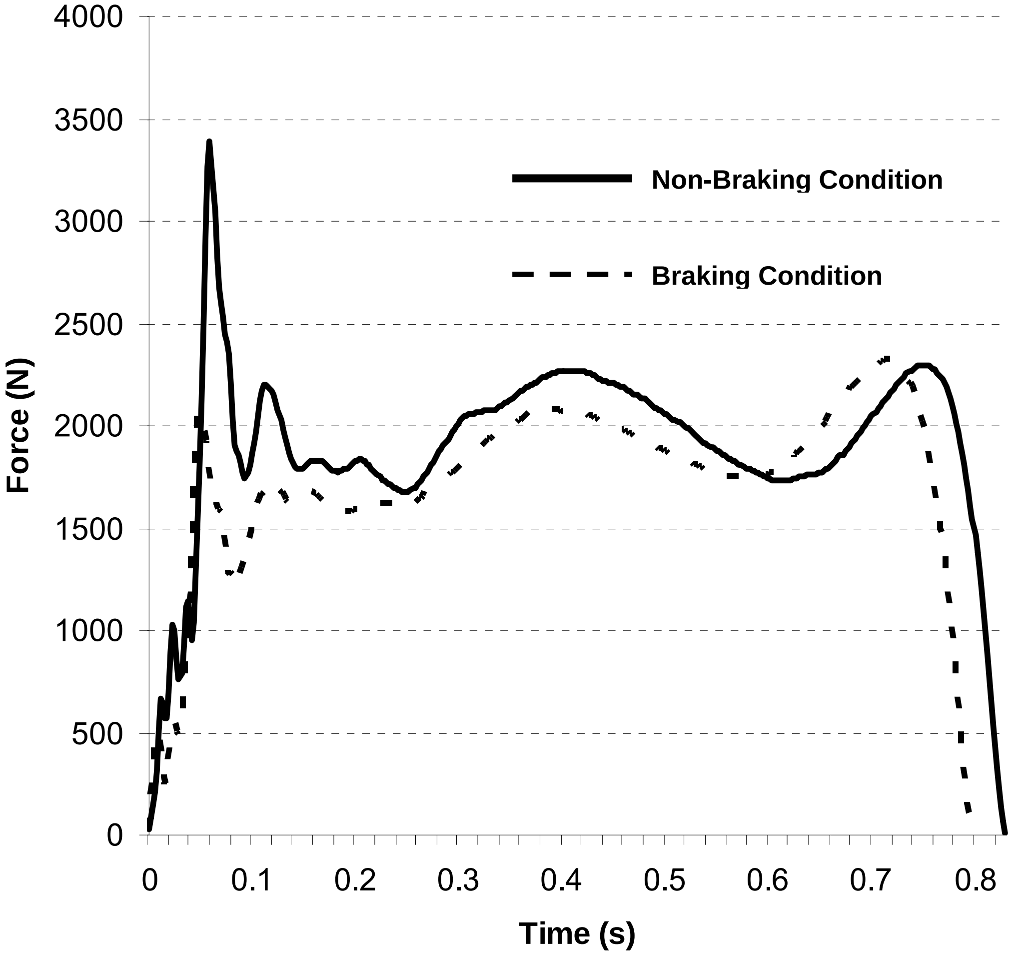

Figure 6.5 Force-time characteristics during a foot contact in each condition.

DISCUSSION

The purpose of this study was to compare the changes in strength, power and athletic performance resulting from weighted jump squat training with and without eccentric braking applied. Further, to quantify the acute effects of the eccentric braking, force-time characteristics of landing were measured over a set of six weighted jump squats.

As we observed differential effects over time for the two conditions, the characteristics of the training stimuli will be discussed first. As presented in Table 6.7 and Figure 6.6, mean force, impulse and impulse for first 50 ms were significantly lower for jumps performed with eccentric braking. This is a result of mechanically reducing the load during the eccentric phase by means of an electromagnetic braking mechanism. The effect is to reduce the preloading of the stretch shortening cycle and as reported by Walshe et al. (1998) which will reduce the total impulse and thus jump height achieved. As can be observed from Figure 6.5, the impact spike was effectively removed by the eccentric braking. Impulse for first 50 ms was also significantly reduced, and this supports previous research (Humphries et al., 1995) suggesting that such systems may be effective for reducing injury risk. Changes in performance adaptations will now be discussed with reference to the kinetic differences between the two conditions.

When the two groups were pooled, there were significant improvements in all performance measures for jump and squat tests of between 3.5 and 13.3% which is similar to other training studies involving weighted jump squats (McBride et al., 2002; Newton et al., 1999). Interestingly, none of isometric or isokinetic measurements showed significant improvement. This most likely reflects the specificity of training in which weighted jump squat (multiple joint, closed kinetic chain task) is much more similar to the jump and squat tests than isometric/isokinetic knee extension/flexion (single joint, open kinetic chain task). Certainly the weighted jump squat training did not transfer well to seated knee extension/flexion performance even though training and testing involve the same muscle groups. The isometric/isokinetic knee extension/flexion testing was designed to tease out neuromuscular changes in the hamstrings and quadriceps resulting from training with Braking versus Non-Braking conditions and in particular eccentric and concentric strength changes as it was hypothesized that the training in Non-Braking condition would have much larger effect on eccentric strength. However, these tests appear unable to detect such specific adaptations to the training.

Despite these comments there was a significant interaction between groups in peak torque during isokinetic knee flexion at 300° /s (Figure 6.4). It could be speculated that exposure to the landing impact caused rapid hamstrings muscle action and this resulted in increased hamstrings contraction strength at the higher isokinetic velocity. Also, high force output at the beginning of the concentric phase might be another reason why NBG improved this measurement more than BG. Bobbert et al. (1996) has discussed why jump height for CMJ is higher than SJ, and stated the higher force at beginning of concentric phase allows CMJ to achieve higher velocity at the end of concentric phase. Since force applied to ground at the beginning of concentric phase should be higher in NBG, thus the velocity at the take off might be higher in this group than BG. If these speculations were true, such rapid muscle action might strengthen the ability to exert high torque during high velocity activity in NBG. However, comparison between the two conditions in terms of angular velocity in hip and knee joints were not made in the present study, thus we cannot make more definitive conclusions.

If the above speculations are true, then a further question is why there was no group × time interaction in peak torque during knee extension at 300°/s. Since the action of weighted jump squat mainly consists of hip and knee extension, the fact there were no effects on knee extensor strength was unexpected although the hamstrings role as hip extensor is quite significant. It may be that quadriceps exhibit a higher trained level compared to hamstrings due to the more frequent use during daily activity, and that is why the training intervention in the present study resulted in changes in hamstring strength, but not quadriceps strength.

On the other hand, BG exhibited larger improvements in peak power relative to body mass during weighted jump squat and peak torque during isometric knee extension at 10˚ (Figure 6.2 and 6.3). In addition, it is noteworthy there was significant improvement in power output during CMJ (both absolute and relative to body mass) in BG, but not in NBG. Possibly, this result was because reduced eccentric load requires greater muscle active force to produce the subsequent jump. Without braking, a subject can utilize the stretch shortening cycle more effectively. They attain a higher preload (Figure 6.5), and this facilitates the concentric phase requiring less active muscle tension. Conversely, when braking is applied, subjects train without the same contribution of stretch shortening cycle and therefore greater contractile force has to be applied. In other words, to produce the same jump height, the Braking condition requires greater emphasis on concentric muscle power output while the Non-Braking condition relies more on the power generated from stretch shortening cycle mechanisms.

To examine whether there was any difference between the adaptations to two different conditions, the present study included several combinations of the test measurements that emphasised different muscle actions (i.e. either concentric or eccentric actions). These combined measurements involved similar muscle groups, range of motion, and velocity, such as CMJ and SJ (Table 6.3), 1RM Sq Con and Sq Ecc-Con (Table 6.4), and isokinetic knee extension and flexion in concentric action and eccentric action at 60°/s (Table 6.6). However, repeated measures two-way ANOVA did not find any significant time × group interaction in any of these measurements. It was hypothesized that BG would not improve CMJ, 1RM Sq Ecc-Con, isokinetic eccentric knee extension and flexion strength as much as NBG due to the eccentric braking during the landing phase. However, the results require us to reject this hypothesis and accept that at least in these relatively untrained subjects, reduced eccentric load does not inhibit neuromuscular adaptations.

The characteristics of stimuli were clearly different between the two conditions (Table 6.7 and Figure 6.5). As a result, we speculate slightly different mechanisms of adaptation. First, training in Non-Braking condition would enhance the strength at high velocity due to higher velocity than in Braking condition. Second, the training in Braking condition would enhance the strength at moderate/low velocity, and isometric condition due to higher contractile force output than in Non-Braking condition. While the mechanism of adaptation might be different between groups, however, the present study could not detect the difference in adaptation except for three variables (i.e. power output relative to body mass during weighted jump squat, isometric peak torque during knee extension at 10°, and isokinetic concentric knee flexion at 300°/s). In the present study, subjects trained for only 8 weeks. However, it could be possible to detect separation in training effect if the period of training intervention was longer. Realistically, practitioners prescribe training programs based on the theory of periodisation (Plisk & Stone, 2003). Thus, exercise, volume and intensity are altered every mesocycle. It is highly unlikely that practitioners prescribe exactly the same type of training more than two consecutive mesocycles in a given macrocycle, but a similar mesocycle is usually repeated in subsequent macrocycles in a cyclic manner (Plisk & Stone, 2003). Thus, it is important to note that athletes in the practical setting might exhibit more specific adaptation to the two different conditions of weighted jump squat training over the longer term (i.e. over several mesocycles, typically multiple years).

In the present study, 8 weeks of weighted jump squat training resulted in significant improvements in 1RM half squat measurements 5.2-7.0% and 9.3-12.6% in NBG and BG (Table 6.4). This finding supports McBride et al. (2002) which used a similar training protocol. In general, it is believed the training modality emphasizing power is not really effective to enhance maximum strength, and that is why practitioners need to take account of both maximum strength and power in their programs (Newton &

Dugan, 2002; Newton & Kraemer, 1994; Newton et al., 1999; Wilson et al., 1993). However, if the trainee does not have a background of resistance training, then introduction of such exercise represents a novel stimulus and possibly will enhance multiple strength qualities concurrently. This finding would be useful information for practitioners working with developmental level athletes. Although there was no statistical significance of group × time interactions, there was a tendency for BG to improve 1RM half squat more than NBG. It is suggested that this is due to the same reasons why NBG improved power output during weighted jump squat and peak torque during isometric knee extension. The reduced eccentric load and thus inhibited stretch shortening cycle required greater reliance on contractile force development and thus increased stimulus to strength development.

The results for the drop jump should be discussed with caution (Table 3) as reliability of this measurement was not high (ICC = 0.41, Table 2). However, a previous study involving highly trained athletes (Newton et al., 1999) reported this test was reliable (ICC > 0.99). The reason why the drop jump test in the present study was so unreliable could be due to the subjects' limited drop jump training background. Unlike trained volleyball players, the subjects in the present study had not experienced the task such as "develop maximum jump height with minimal ground contact" in their normal activities. Thus, to examine the true effect of the weighted jump squat training with and without eccentric braking on drop jump performance, future studies need to involve subjects more accustomed to this test.

To our knowledge, the study reported by Hoffman et al. (2005) is the only study thus far on this topic. They compared the effects of weighted jump squat training with and without eccentric braking on strength, power and athletic performance, and reported that the weighted jump squat without the braking was more effective than that with the braking to improve 1RM power clean and squat. In the present study, improvement in 1RM half squat measurements in NBG was not superior to BG, so our results do not support that of Hoffman et al. (2005). However, it is difficult to directly compare these two studies since there are marked differences such as: 1) the subjects in Hoffman et al. (2005) were highly trained football players while the subjects in the present study were untrained students; 2) the training intervention in Hoffman et al. (2005) was combined with normal football strength and conditioning program while subjects in the present study did not participate in any competitive sport training; 3) The movement of weighted jump squat performed in Hoffman et al. (2005) was controlled by machine while the subjects in the present study used free weights and controlled their movement using their synergist and antagonist muscle groups; 4) The subjects in Hoffman et al. (2005) used 70% of 1RM load while subjects in the present study used 30% of 1RM load. Some or all of these factors may explain the different results to that of Hoffman et al. (2005) and the present study. Particularly, if one training mode is combined with other types of training, the adaptation of combined training modes could be different from the one training mode alone (Adams et al., 1992; Harris et al., 2000; Newton & Kraemer, 1994). Since weighted jump squat training is often combined with other types of resistance-training exercises such as traditional weight-training exercises (e.g. squat, power clean) and plyometric exercises in the practical setting (Hoffman et al., 2005), it is not definitive that the finding of the present study can be directly applied to the practical setting. Hence, future studies bridging the gap between controlled laboratory based experiments and realistic training scenarios are warranted.

In summary, this study compared the effects of two different conditions of weighted jump squat training, with and without an eccentric braking mechanism. The force-time characteristics of the exercise were markedly different with regard to mean force, impulse and impulse for first 50 ms, and this explains the differential training effects. Interestingly, while isometric strength (peak torque during isometric knee extension at 10°) and power output during relatively slow movement (weighted jump squat) improved more in BG, strength at high velocity (peak torque during isokinetic knee flexion at 300°/s) improved more in NBG. It is speculated that the use of the braking mechanism during eccentric phase decreases velocity of the movement but emphasizes contractile force production during concentric phase of weighed jump squat. This further supports the highly specific nature of training adaptation.

PRACTICAL APPLICATIONS

In the position statement from National Strength and Conditioning Association (1993), it is documented that “only athletes who have already achieved high levels of strength through standard resistance training should engage in plyometric drills.” This statement does not necessarily apply for all plyometric drills as lower intensity exercises will benefit the athlete and do not require a large strength base. However, a certain level of physical preparation is essential for some high intensity plyometric drills such as drop jump and/or unilateral bounding. Since weighted jump squat training without eccentric braking has similar characteristics to plyometric drills (i.e. utilization of stretch shortening cycle and absorption of high landing impact), practitioners should carefully consider the training background of athletes and whether the athletes would tolerate the landing impact during the weighted jump squat. While the subjects in the present study tolerated the 30% of 1RM half squat load without any injuries, one must remember this load is not necessarily safe for everybody if weighted jump squat is performed without eccentric braking. Particularly for competitive athletes playing sports with chronic injuries, even 30% of 1RM half squat load may possibly aggravate their injuries. Therefore, practitioners should consult with their medical staff and monitor the athletes closely especially when they first introduce weighted jump squat training without eccentric braking. If any symptoms of injuries appear, such athletes should either reduce loads or utilize eccentric braking. Humphries et al. (1995) suggested the possible risk of injuries due to the landing impact in weighted jump squat without eccentric braking, and encourage use of the braking mechanism to reduce eccentric load during landing phase for injury prevention and these findings are supported by the current study. Thus, until athletes acquire a certain level of strength, practitioners should consider reducing eccentric loading during landing phase by using braking mechanisms or other training modifications as it appears that comparable improvements in jump performance are attained, at least over a relatively short 8 week period. Then, once the athletes attain a certain level of strength, practitioners may select the training mode to meet their training purposes. On one hand, during the general preparation phase, weighted jump squat with a braking mechanism may cause larger adaptation in strength at low/moderate velocity. On the other hand, during the specific preparation phase, weighted jump squat without a braking mechanism may cause larger adaptation in strength at high velocity. Once a practitioner decides to introduce weighted jump squat without eccentric braking, it would be wise to start with light loads and allow the athletes to adapt to this new stimulus. Baker and Nance (1999b) suggested there should be a minimal risk of injuries due to this form of exercise as long as the application of overload is gradual and progressive. For example, if an athlete’s 1RM half squat is 200 kg, the practitioner may spend the first few sessions with 20 kg, another few sessions with 40 kg, and then increase the load up to 60 kg (i.e. 30% of 1RM).

CHAPTER 7

SUMMARY AND CONCLUSIONS

The major purpose of this thesis was to evaluate how power capability should be assessed, and how it should be improved. Through a series of four studies, this thesis made the following contributions to the body of knowledge.

Study 1 examined the reliability of power output and its related variables. In addition, this study also examined the influence of reducing sampling frequencies on validity and reliability. First of all, this study confirmed that peak power is a highly reliable measurement, thus this variable was measured as one of the most important mechanical quantities throughout the subsequent Studies 2, 3 and 4. In addition, Study 1 found that the differences between power and its related variables calculated from force-time data sampled at a rate of 500 Hz and data sampled at 400, 250, and 200 Hz were trivial. The capacity of sampling frequency of the laboratory based force platform used in Studies 1 and 4 was 500 Hz, and the portable force platform used in Studies 2 and 3 was 200 Hz. Thus, the validity of the data sampled at a rate of 200 Hz in Studies 2 and 3 was confirmed in Study 1. In general, a force platform with high portability often has low sampling frequency. However, even with the limited sampling frequency, the portability of equipment could be the most important issue for the scientists and practitioners who test their athletes at the training site, not the laboratory. Therefore, the finding of Study 1 is especially significant for the applied setting.

Study 2 was an investigation of whether there was any difference between the power output values obtained from four different methods; displacement-time data and mass of barbell, displacement-time data and mass of system, GRF-time data and mass of system, and combination of GRF-time and displacement-time data. Theoretically, calculating power from GRF-time data is the most logical method, thus the value obtained from this method was considered as a reference. This study revealed the power output values applied to COG of the system obtained from the barbell displacement-time data only and combination of the barbell displacement-time and the GRF-time data were significantly different from the value obtained from the GRF-time data only. Therefore, it is recommended that scientists and practitioners only use a force platform to measure power output during the weighted jump squat and hang power clean when possible. Based on the finding in this study, power output was calculated from GRF-time data in Studies 3 and 4.

While measuring power output is the most appropriate way to assess the power capability of athletes, not many practitioners have access to a force platform. Therefore, it is critical for those practitioners to establish valid test measurements to assess power, or at least underpinning strength qualities. Study 3 was an attempt to reveal whether an athlete who possesses higher performance in hang power clean also performs better in jumping, sprinting and COD compared to an athlete who possesses lower performance in this movement. For a better understanding, this study also examined if there were any underlying strength qualities that were common to the hang power clean and jumping, sprinting and COD. It was found that the group possessing the higher 1RM hang power clean relative to the body mass also possessed higher maximum strength, power, and performance of jumping and sprinting. However, this test could not differentiate the good and poor performance of COD. There were significant correlations between the 1RM hang power clean relative to the subject's body mass, maximum strength, power, and performance of jumping and sprinting, but there was no correlation between the 1RM hang power clean relative to the subject's body mass and COD although there were significant correlations between absolute value and the performance of COD. Therefore, 1RM hang power clean can be considered as a useful test to quantify an athlete's neuromuscular performance, and thus appears to be a measure of underpinning strength qualities for power based athletic performance like jumping and sprinting. On the other hand, the performance of COD is not significantly related to most of the measurements of strength and power. Hence, a holistic approach, especially to take account of its skill aspects, is required to improve the performance of COD.

While Studies 1, 2, and 3 investigated the methodological issues of how scientists and practitioners should assess athletes' capability of power, Study 4 investigated the impact of reducing the eccentric load to reduce injury risk on power development from jump squat training. From previous studies (Newton et al., 1999; Wilson et al., 1993), it is apparent that using weighted jump squats is an effective form of training modality to improve power. However, whether one should use eccentric braking or not had not been fully investigated. Study 4 was a comparison of the effects of two different conditions of weighted jump squat training, with or without an eccentric braking mechanism. The force-time characteristics of these exercises were markedly different with regard to mean force, impulse and impulse for first 50 ms, and this explains the differential training effects. Interestingly, while isometric strength (peak torque during isometric knee extension at 10°) and power output during a relatively slow movement (weighted jump squat) improved more in weighted jump squat training with eccentric braking, strength at high velocity (peak torque during isokinetic knee flexion at 300°/s) improved more in the training without eccentric braking. It is speculated that the use of the braking mechanism during eccentric phase decreases velocity of the movement but emphasizes contractile force production during the concentric phase of weighed jump squat. This further supports the highly specific nature of training adaptation. One limitation of this study is the characteristics of subjects. Since Study 4 involved only a recreationally trained population, there must be caution when the findings from this study are applied to competitive athletes.

By combining all four studies together, this thesis would suggest the following practical applications. First of all, Study 4 confirmed that weighted jump squat is effective to enhance lower extremity power, and suggested practitioners to carefully consider the characteristics of each form of resistance training exercise. For example, during the general preparation phase, weighted jump squat with a braking mechanism may cause larger adaptations in strength at low/moderate velocity, and this training would be accompanied with lower injury risk. However, during the specific preparation phase, weighted jump squat without a braking mechanism may cause larger adaptation in strength at high velocity. With such a long term approach, practitioners need to monitor athletes frequently (e.g. once every 4 weeks) and accurately assess their power output capability. Based on Study 2, the force platform seems to be the most valid (i.e. high reliability and validity) equipment to measure power output, thus scientists and practitioners should utilize this piece of equipment where possible. While the higher sampling frequencies are better for analysis, Study 1 suggests a minimum sampling frequency of 200 Hz can be used without meaningful impact on validity or reliability of measurement. If portability, data file size, or price is the limiting factor, scientists and practitioners may consider sampling at this rate or higher. In the case of no force or displacement testing equipment being available, practitioners may consider 1RM of weightlifting exercises (e.g. hang power clean) to be a valid test of power and athletic performance.

CHAPTER 8

DIRECTIONS FOR FUTURE RESEARCH

Several research questions have arisen from this thesis and the following is a discussion of research questions that could be investigated in future studies.

Validity and reliability of the position transducer to measure power output during weighted jump squat with using the Smith machine

In Study 2, considerable margin of error was found in the methods assuming that COG of the barbell and lifter move in parallel during the weighted jump squat. While weighted jump squat was performed using free weight in this study, quite few athletes perform weighted jump squat using Smith machines. In a Smith machine, displacement of the barbell is limited in vertical direction only, thus it may not cause as much error as that observed in weighted jump squat with free weight. From such rationale, it would be of interest for scientists and practitioners to investigate the validity and reliability of position transducers to measure power output during weighted jump squat using Smith machines.

Comparison of kinematic characteristics of weighted jump squat with and without eccentric braking

In Study 4, the training effect and GRF-time characteristics of two different types of weighted jump squat were compared. It was found that weighted jump squat training without eccentric braking was more effective to develop strength at high velocity, so it is speculated that the high GRF during the eccentric phase enhances the velocity of subsequent concentric phase. However, the kinetic data collected in this study were not synchronized with any kinematic data. That is, it was not confirmed whether the high eccentric load actually enhanced the subsequent concentric phase in terms of joint angular velocity. In future study, it is important to examine the kinematic characteristics (e.g. linear velocity of the barbell, angular velocity of hip, knee, and ankle joints) of two different weighted jump squats using video cameras synchronized with the force platform, to provide greater elucidation of the mechanisms of differential training effects found in Study 4.

Comparison of training effects of weighted jump squat training with and without eccentric braking on sports specific performance consisting of concentric only actions.

Hoffman et al. (2005) has reported the effects of eccentric braking on weighted jump squat training on strength, power and athletic performance of competitive American football players. However, there is no previous study in this topic focusing on the sports in which their task predominantly consists of concentric muscle action (e.g. rowing, cycling, and swimming). In such sports, rapid eccentric load may not be specific to the athlete's task, so that reducing the load in eccentric phase and training with emphasis of concentric action might be more specific to the target movements.

Effects of weightlifting exercises on strength, power and athletic performance

As explained in Chapter 5, the athletes that possess high performance in weightlifting exercises also possess high strength, power and athletic performance. Thus, an important research question would be whether training with the weightlifting exercises actually improves strength, power and athletic performance. At present, three studies (Hoffman et al., 2004; Stone et al., 1980; Tricoli et al., 2005) have investigated this research question, but further controlled studies are required. In general, learning proper technique of weightlifting exercises is not as easy as that of weighted jump squat. It seems to be one of the reasons why there is only three studies (Hoffman et al., 2004; Stone et al., 1980; Tricoli et al., 2005) that have utilized weightlifting exercises while many more studies have been completed with weighted jump squat (Lyttle et al., 1996; McBride et al., 2002; McEvoy & Newton, 1998; McGuigan et al., 2003; Newton et al., 2002; Newton et al., 1999; Newton et al., 2006; Wilson et al., 1993). Since there is a time period required to learn the techniques of weightlifting exercises, it is questionable whether it is appropriate to design a training study using untrained university students or similar with short duration training interventions (e.g. 8 weeks) to truly investigate the changes in strength qualities and sports performance. On the other hand, it would be a meaningful contribution if practitioners record and analyze the athletes' training logs and examine whether the improvement of weightlifting exercises corresponds to the improvement of strength, power and athletic performance.

Previous research (Cormie et al., 2007b; Kawamori & Haff, 2004) suggests considering the specificity of training in terms of the mass which the athletes need to overcome during their sport. For example, weighted jump squat with relatively light load to be specific for sprinting (the mass required to overcome is body mass only), and weighted jump squat with relatively heavy load to be specific for tackling or blocking in football (the mass required to overcome is the opponent's body mass in addition to own body mass). In general, weightlifting exercise allows athletes to handle a lot heavier weight than weighted jump squat, so that weightlifting exercises might be very specific and effective training to improve athletes' blocking or tackling performance in football and similar combative sports. In future research, it would be interesting to examine whether there are any relationships between the improvement of weightlifting exercise performance (e.g. measured by 1RM) and improvement of blocking or tacking performance (e.g. rated by coaches) in competitive football athletes.

Comparison of biomechanical characteristics between impact force at landing in weightlifting exercises and weighted jump squat

While two studies (Canavan et al., 1996; Garhammer & Gregor, 1992) have investigated the characteristics of GRF during propulsive phase of vertical jump and weightlifting exercises, no previous study has investigated those during landing phase. On one hand, the vertical displacement of system COG during weightlifting exercises is much smaller than that during weighted jump squat (Garhammer, 1993). On the other hand, the weight the athletes can lift would be much heavier in weightlifting exercises than that in weighted jump squat unless eccentric braking is applied. Hence, it is speculated that the impact force during weightlifting exercises could consist of larger mass and smaller acceleration compared to that during weighted jump squat. As investigated in Study 4, the impact force at landing is one of the important factors to consider for designing strength training programs. Therefore, it would be important to investigate the characteristics of GRF-time curves (e.g. impulse for the first 50 ms) during the landing phase of weightlifting exercises. Furthermore, it would be of interest among scientists and practitioners to determine the adaptations induced if athletes are exposed to the different types of impact force at landing phase over chronic training exposures (i.e. high mass × low acceleration in weightlifting exercises vs. low mass × high acceleration in weighted jump squat).

REFERENCES

Adams, K., O'Shea, J. P., & Climstein, M. (1992). The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *Journal of Applied Sport Science Research, 6*(1), 36-41.

Baker, D. (2001a). Acute and long-term power response to power training: Observations on the training of an elite power athlete. *Strength and Conditioning Journal, 23*(1), 47-56.

Baker, D. (2001b). The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players. *Journal of Strength and Conditioning Research, 15*(2), 172-177.

Baker, D. (2002). Differences in strength and power among junior-high, senior-high, college-age, and elite professional rugby league players. *Journal of Strength and Conditioning Research, 16*(4), 581-585.

Baker, D. (2007). Using full acceleration and velocity-dependent exercises to enhance power training. *Strength and Conditioning Coach, 15*(2), 16-21.

Baker, D., & Nance, S. (1999a). The relation between running speed and measures of strength and power in professional rugby league players. *Journal of Strength and Conditioning Research, 13*(3), 230-235.

Baker, D., & Nance, S. (1999b). The relation between strength and power in professional rugby league players. *Journal of Strength and Conditioning Research, 13*(3), 224-229.

Baker, D., Nance, S., & Moore, M. (2001a). The load that maximizes the average mechanical power output during explosive bench press throws in highly trained athletes. *Journal of Strength and Conditioning Research, 15*(1), 20-24.

Baker, D., Nance, S., & Moore, M. (2001b). The load that maximizes the average mechanical power output during jump squats in power-trained athletes. *Journal of Strength and Conditioning Research, 15*(1), 92-97.

Baker, D., & Newton, R. U. (2006). Adaptations in upper-body maximal strength and power output resulting from long-term resistance training in experienced strength-power athletes. *Journal of Strength and Conditioning Research, 20*(3), 541-546.

Barker, M., Wyatt, T. J., Johonson, R. L., Stone, M. H., O'Bryant, H. S., Poe, C., & Kent, M. (1993). Performance factors, psychological assessment, physiological characteristics, and football playing ability. *Journal of Strength and Conditioning Research, 7*(4), 224-233.

Baumgartner, T. A., & Chung, H. (2001). Confidence limits for intraclass reliability coefficients. *Measurement in Physical Education and Exercise Science, 5*, 179-188.

Behm, D. G. (1995). Neuromuscular implications and applications of resistance training. *Journal of Strength and Conditioning Research, 9*(4), 264-274.

Behm, D. G., & Sale, D. G. (1993). Intended rather than actual movement velocity determines velocity-specific training response. *Journal of Applied Physiology, 74*(1), 359-368.

Blazevich, A. J., Gill, N. D., Bronks, R., & Newton, R. U. (2003). Training-specific muscle architecture adaptation after 5-wk training in athletes. *Medicine and Science in Sports and Exercise, 35*(12), 2013-2022.

Bobbert, M. F., Gerritsen, K. G. M., Litjens, M. C. A., & Van Soest, A. J. (1996). Why is countermovement jump height greater than squat jump height? *Medicine and Science in Sports and Exercise, 28*(11), 1402-1412.

Bobbert, M. F., & Van Soest, A. J. (1994). Effects of muscle strengthening on vertical jump height: a simulation study. *Medicine and Science in Sports and Exercise, 26*(8), 1012-1020.

Brandenburg, J. P., & Docherty, D. (2002). The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. *Journal of Strength and Conditioning Research, 16*(1), 25-32.

Caiozzo, V. J., Perrine, J. J., & Edgarton, V. R. (1981). Training-induced alterations of the in vivo force-velocity relationships of human muscles. *Journal of Applied Physiology, 51*(3), 750-754.

Caldwell, G. E., Robertson, G. E., & Whittlesey, S. N. (2004). Force and their measurement. In D. G. E. Robertson, G. E. Caldwell, J. Hamill, G. Kamen & S. N. Whittlesey (Eds.), *Research Methods in Biomechanics* (pp. 227-238). Champaign, IL: Human Kinetics.

Canavan, P. K., Garrett, G. E., & Armstrong, L. E. (1996). Kinematic and kinetic relationships between an Olympic-style lift and the vertical jump. *Journal of Strength and Conditioning Research, 10*(2), 127-130.

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., Newton, R. U., Harman, E. A., Sands, W. A., & Stone, M. H. (2004). The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *Journal of Strength and Conditioning Research, 18*(3), 534-539.

Cavagna, G. A. (1977). Storage and utilization of elastic energy in skeletal muscle. *Exercise and Sport Science Reviews, 5*, 89-129.

Chiu, L. Z. F., Fry, A. C., Weiss, L. W., Schilling, B. K., Brown, L. E., & Smith, S. L. (2003). Postactivation potentiation response in athletic and recreationally trained individuals. *Journal of Strength and Conditioning Research, 17*(4), 671-677.

Chiu, L. Z. F., & Schilling, B. K. (2005). A primer or weightlifting: From sport to sports training. *Strength and Conditioning Journal, 27*(1), 42-48.

Chiu, L. Z. F., Schilling, B. K., Fry, A. C., & Weiss, L. W. (2004). Measurement of resistance exercise force expression. *Journal of Applied Biomechanics, 20*, 204-212.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2007a). Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics, 23*, 103-118.

Cormie, P., McBride, J. M., & McCaulley, G. O. (In Press). Power-time, force-time and velocity-time curve analysis during the jump squat: Impact of load. *Journal of Applied Biomechanics*.

Cormie, P., McCaulley, G. O., Triplett, N. T., & McBride, J. M. (2007b). Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports and Exercise, 39*(2), 340-349.

Cronin, J., & Sleivert, G. (2005). Challenges in understanding the influence of maximal power training on improving athletic performance. *Sports Medicine, 35*(3), 213-234.

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of Strength and Conditioning Research, 19*(2), 349-357.

Derrick, T. R. (2004). Signal processing. In D. G. E. Robertson, G. E. Caldwell, J. Hamill, G. Kamen & S. N. Whittlesey (Eds.), *Research Methods in Biomechanics* (pp. 227-238). Champaign, IL: Human Kinetics.

Devita, P., & Skelly, W. A. (1990). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine and Science in Sports and Exercise, 24*(1), 108-115.

Dierking, J. K., & Bemben, M. G. (1998). Delayed onset muscle soreness. *Strength and Conditioning, 20*(4), 44-48.

Doan, B. K., Newton, R. U., Marsit, J. L., Triplett-McBride, N. T., Koziris, L. P., Fry, A. C., & Kraemer, W. J. (2002). Effects of increased eccentric loading on bench press 1RM. *Journal of Strength and Conditioning Research, 16*(1), 9-13.

Dugan, E., Doyle, T. L. A., Humphries, B., Hasson, C. J., & Newton, R. U. (2004). Determining the optimal load for jump squats: A review of methods and calculations. *Journal of Strength and Conditioning Reserach, 18*(3), 668-674.

Ebben, W. P., & Blackard, D. O. (2001). Strength and conditioning practice of National Football League strength and conditioning coaches. *Journal of Strength and Conditioning Research, 15*(1), 48-58.

Ebben, W. P., Carroll, R. M., & Simenz, C. (2004). Strength and conditioning practice of National Hockey League strength and conditioning coaches. *Journal of Strength and Conditioning Research, 18*(4), 889-897.

Enoka, R. M. (1994). *Neuromechanical Basis of Kinesiology* (2nd ed.). Champaign, IL: Human Kinetics.

Fleck, S. J. (2002). Periodization of training. In W. J. Kraemer & K. Häkkinen (Eds.), *Strength Training for Sport* (pp. 55-68). Oxford: Blackwell Science.

Fleck, S. J., & Kraemer, W. J. (2004a). Advanced training strategies. In S. J. Fleck & W. J. Kraemer (Eds.), *Designing Resistance Training Programs* (3rd ed., pp. 209-239). Champaign, IL: Human Kinetics.

Fleck, S. J., & Kraemer, W. J. (2004b). Basic principles of resistance training and exercise prescription. In S. J. Fleck & W. J. Kraemer (Eds.), *Designing Resistance Training Programs* (3rd ed., pp. 3-12). Champaign, IL: Human Kinetics.

Fleck, S. J., & Kraemer, W. J. (2004c). Neuromuscular physiology and adaptations to resistance training. In S. J. Fleck & W. J. Kraemer (Eds.), *Designing Resistance Training Programs* (3rd ed., pp. 53-128). Champaign, IL: Human Kinetics.

Fry, A. C., & Kraemer, W. J. (1991). Physical performance characteristics of American collegiate football players. *Journal of Applied Sport Science Research, 5*(3), 126-138.

Fry, A. C., Kraemer, W. J., Weseman, C. A., Conroy, B. P., Gordon, S. E., Hoffman, J. R., & Maresh, C. A. (1991). The effects of an off-season strength and conditioning program on starters and non-starters in women's intercollegiate volleyball. *Journal of Strength and Conditioning Research, 5*(4), 174-181.

Fry, A. C., & Newton, R. U. (2002). A brief history of strength training and basic principles and concepts. In W. J. Kraemer & K. Häkkinen (Eds.), *Strength Training for Sport* (pp. 55-68). Oxford: Blackwell Science.

Fry, A. C., Schilling, B. K., Staron, R. S., Hagerman, F. C., Hikida, R. S., & Thrush, J. T. (2003a). Muscle fiber characteristics and performance correlates of male Olympic-style weightlifters. *Journal of Strength and Conditioning Research, 17*(4), 746-754.

Fry, A. C., Webber, J. M., Weiss, L. W., Harber, M. P., Vaczi, M., & Pattison, N. A. (2003b). Muscle fiber characteristics of competitive power lifters. *Journal of Strength and Conditioning Research, 17*(2), 402-410.

Garhammer, J. (1993). A review of power output studies of Olympic and powerlifting: Methodology, performance prediction, and evaluation tests. *Journal of Strength and Conditioning Research, 7*(2), 76-89.

Garhammer, J., & Gregor, R. (1992). Propulsion forces as a function of intensity for weightlifting and vertical jumping. *Journal Of Applied Sport Science Research, 6*(3), 129-134.

Haff, G. G., & Potteiger, J. A. (2001). A brief review: Explosive exercises and sports performance. *Strength and Conditioning Journal, 23*(3), 13-20.

Haff, G. G., Stone, M., O'Bryant, H. S., Harman, E., Dian, C., Johnson, R., & Han, K.-H. (1997). Force-time dependent characteristics of dynamic and isometric muscle actions. *Journal of Strength and Conditioning Research, 11*(4), 269-272.

Haff, G. G., Whitley, A., McCoy, L., O'Bryant, H. S., Kilgore, J. L., Haff, E. E., Pierce, K., & Stone, M. H. (2003). Effects of different set configurations on barbell velocity and displacement during a clean pull. *Journal of Strength and Conditioning Research, 17*(1), 95-103.

Häkkinen, K., Alen, M., & Komi, P. V. (1985). Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiologica Scandinavica, 125*, 573-585.

Häkkinen, K., Pakarinen, A., Alen, M., Kauhanen, H., & Komi, P. V. (1988). Neuromuscular and hormonal adaptations in athletes to strength training in two years. *Journal of Applied Physiology, 65*, 2406-2412.

Hamill, J., & Selbie, W. S. (2004). Three-dimensional kinetics. In D. G. E. Robertson, G. E. Caldwell, J. Hamill, G. Kamen & S. N. Whittlesey (Eds.), *Research Methods in Biomechanics* (pp. 227-238). Champaign, IL: Human Kinetics.

Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. *Medicine and Science in Sports and Exercise, 22*(6), 825-833.

Harman, E. A., Rosenstein, M. T., Frykman, P. N., Rosenstein, R. M., & Kraemer, W. J. (1991). Estimation of human power output from vertical jump. *Journal of Applied Sport Science Research, 5*(3), 116-120.

Harris, G. R., Stone, M. H., O'Bryant, H. S., Proulx, C. M., & Johnson, R. L. (2000). Short-term performance effects of high power, high force, or combined weight-training methods. *Journal of Strength and Conditioning Research, 14*(1), 14-20.

Hoffman, J. R. (1996). Relationship between athletic performance tests and playing time in elite college basketball players. *Journal of Strength and Conditioning Research, 10*(2), 67-71.

Hoffman, J. R., Cooper, J., Wendell, M., & Kang, J. (2004). Comparison of Olympic vs. traditional power lifting training programs in football players. *Journal of Strength and Conditioning Research, 18*(1), 129-135.

Hoffman, J. R., Nusse, V., & Kang, J. (2003). The effect of an intercollegiate soccer game on maximal power performance. *Canadian Journal of Applied Physiology, 28*(6), 807-817.

Hoffman, J. R., Ratamess, N. A., Cooper, J. J., Kang, J., Chilakos, A., & Faigenbaum, A. D. (2005). Comparison of loaded and unloaded jump squat training on strength/power performance in college football players. *Journal of Strength and Conditioning Research, 19*(4), 810-815.

Hopkins, W. G. (2002). A new view of statistics. *http://sportsci.org/resource/stats/index.html [Accessed June 27, 2007]*.

Hori, N., Andrews, W. A., Nosaka, K., McGuigan, M. R., & Newton, R. U. (In press). Observation of load-power curves in the hang power clean. *Strength and Conditioning Coach.*

Hori, N., Newton, R. U., Nosaka, K., & McGuigan, M. R. (2006). Comparison of different methods of determining power output in weightlifting exercises. *Strength and Conditioning Journal, 28*(2), 34-40.

Hori, N., Newton, R. U., Nosaka, K., & Stone, M. H. (2005). Weightlifting exercises enhance athletic performance that requires high-load speed strength. *Strength and Conditioning Journal, 27*(4), 50-55.

Hortobagyi, T., Devita, P., Money, J., & Barrier, J. (2001). Effects of standard and eccentric overload strength training in young women. *Medicine and Science in Sports and Exercise, 33*(7), 1206-1212.

Humphries, B. J., Newton, R. U., & Wilson, G. J. (1995). The effect of a braking device in reducing the ground impact forces inherent in plyometric training. *International Journal of Sports Medicine, 16*(2), 129-133.

James, R. C., & Bates, B. T. (2003). Classification and comparison of biomechanical response strategies for accommodating landing impact. *Journal of Applied Biomechanics, 19*, 106-118.

Kaminski, T. W., Wabbersen, C. V., & Murphy, R. M. (1998). Concentric versus enhanced eccentric hamstring strength training: Clinical implications. *Journal of Athletic Training, 33*(3), 216-221.

Kaneko, M., Fuchimoto, T., Toji, H., & Suei, K. (1983). Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scandinavian Journal of Sports Science, 5*(2), 50-55.

Kawakami, Y., Abe, T., Kuno, S., & Fukunaga, T. (1995). Training-induced changes in muscle architecture and specific tension. *European Journal of Applied Physiology, 72*, 37-43.

Kawamori, N., Crum, A. J., Blumert, P. A., Kulik, J. R., Childers, J. T., Wood, J. A., Stone, M. H., & Haff, G. G. (2005). Influence of different relative intensities on power output during the hang power clean: Identification of the optimal load. *Journal of Strength and Conditioning Research, 19*(3), 698-708.

Kawamori, N., & Haff, G. G. (2004). The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research, 18*(3), 675-684.

Kawamori, N., & Newton, R. U. (2006). Velocity specificity of resistance training: Actual movement velocity vs. intention to move explosively. *Strength and Conditioning Journal, 28*(2), 86-91.

Kearns, C. F., Abe, T., & Brechue, W. F. (2000). Muscle enlargement in sumo wrestlers includes increased muscle fascicle length. *European Journal of Applied Physiology, 83*, 289-296.

Klavora, P. (2000). Vertical-jump tests: A critical review. *Strength and Conditioning Journal, 22*(5), 70-75.

Knuttgen, H. G., & Kraemer, W. J. (1987). Terminology and measurement in exercise performance. *Journal of Applied Sport Science Research, 1*(1), 1-10.

Komi, P. V. (2003). Stretch-shortening cycle. In P. V. Komi (Ed.), *Strength and Power in Sport* (2nd ed., pp. 184-202). Oxford: Blackwell Science Ltd.

Kumagai, K., Abe, T., Brechue, W. F., Ryusei, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *Journal of Applied Physiology, 88*, 811-816.

Little, T., & Williams, A. (2005). Specificity of acceleration, maximum speed, and agility in professional soccer players. *Journal of Strength and Conditioning Research, 19*(1), 76-78.

Lyttle, A. D., Willson, G. J., & Ostrowski, K. J. (1996). Enhancing performance: Maximal power versus combined weights and plyometrics training. *Journal of Strength and Conditioning Research, 10*(3), 173-179.

Markovic, G. (2007). Does plyometric training improve vertical jump height? A meta-analytical review. *British Journal of Sports Medicine, 41*, 349-355.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *Journal of Strength and Conditioning Research, 13*(1), 58-66.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *Journal of Strength and Conditioning Research, 16*(1), 75-82.

McEvoy, K. P., & Newton, R. U. (1998). Baseball throwing speed and base running speed: the effects of ballistic resistance training. *Journal of Strength and Conditioning Research, 12*(4), 216-221.

McGinnis, P. M. (2005). Technology in biomechanics. In P. M. McGinnis (Ed.), *Biomechanics of Sport and Exercise* (2nd ed., pp. 361-370). Champaign, IL: Human Kinetics.

McGuigan, M. R., Doyle, T. L., Newton, M., Edwards, D. J., Nimphius, S., & Newton, R. U. (2006). Eccentric utilization ratio: Effect of sport and phase of training. *Journal of Strength and Conditioning Research, 20*(4), 992-995.

McGuigan, M. R., Sharman, M. J., Newton, R. U., Davie, A. J., Murphy, A. J., & McBride, J. M. (2003). Effect of explosive resistance training on titin and myosin heavy chain isoforms in trained subjects. *Journal of Strength and Conditioning Research, 17*(4), 645-651.

Moore, C. A., Fry, A. C., Melton, A. J., Weiss, L. W., & Rosato, F. D. (2003). Power and velocity production for different relative intensities for the hang power clean exercise. *Journal of Strength and Conditioning Research, 17*(4), e12.

Moore, C. A., & Schilling, B. K. (2005). Theory and application of augmented eccentric loading. *Strength and Conditioning Journal, 27*(5), 20-27.

Moritani, T. (1992). Time course of adaptations during strength and power training. In P. V. Komi (Ed.), *Strength and Power in Sport* (pp. 266-278). Oxford: Blackwell Scientific Publications.

Moritani, T., & deVries, H. A. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *American Journal of Physical Medicine, 58*(3), 115-130.

Moss, B. M., Refsnes, P. E., Abildgaard, A., Nicolaysen, K., & Jensen, J. (1997). Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *European Journal of Applied Physiology, 75*, 193-199.

NationalStrengthandConditioningAssociation. (1993). Position statement: Explosive/plyometric exercises. *National Strength and Conditioning Association Journal, 15*(3), 16.

Newton, R. U. (1997). *Expression and development of maximal muscle power.* Southern Cross university, Lismore, Australia.

Newton, R. U., & Dugan, E. (2002). Application of strength diagnosis. *Strength and Conditioning Journal, 24*(5), 50-59.

Newton, R. U., Häkkinen, K., Häkkinen, A., McCormick, M., Volek, J., & Kraemer, W. J. (2002). Mixed-methods resistance training increases power and strength of young and older man. *Medicine and Science in Sports and Exercise, 34*(8), 1367-1375.

Newton, R. U., & Kraemer, W. J. (1994). Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength and Conditioning, 16*(4), 20-31.

Newton, R. U., Kraemer, W. J., & Häkkinen, K. (1999). Effects of ballistic training on preseason preparation of elite volleyball players. *Medicine and Science in Sports and Exercise, 31*(2), 323-330.

Newton, R. U., Kraemer, W. J., Häkkinen, K., Humphries, B. J., & Murphy, A. J. (1996). Kinematics, kinetics, and muscle activation during explosive upper body movements. *Journal of Applied Biomechanics, 12*, 31-43.

Newton, R. U., Rogers, R. A., Volek, J. S., Häkkinen, K., & Kraemer, W. J. (2006). Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *Journal of Strength and Conditioning Research, 20*(4), 955-961.

Nigg, B. M. (1985). Loads in selected sport activities-An overview. In D. A. Winter & R. W. Norman (Eds.), *Biomechanics IX-B* (pp. 91-96). Champaign, IL: Human Kinetics.

Nigg, B. M., Denoth, J., & Neukomm, P. A. (1981). Quantifying the load on the human body: Problems and some possible solutions. In A. Morecki, K. Fidelus, K. Kedzior & A. Wit (Eds.), *Biomechanics VII-B* (pp. 88-99). Baltimore, ML: University Press.

Norton, K., Marfell-Jones, M., Whittingham, N., Kerr, D., Carter, L., Saddington, K., & Gore, C. (2000). Anthropometric assessment protocols. In C. Gore (Ed.), *Physiological Tests for Elite Athletes* (pp. 66-85). Champaign, IL: Human Kinetics.

Nosaka, K., & Clarkson, P. M. (1995). Muscle damage following repeated bouts of high force eccentric exercise. *Medicine and Science in Sports and Exercise, 27*(9), 1263-1269.

Pette, D., & Vrbova, G. (1992). Adaptation of mammalian skeletal muscle fibers to chronic electrical stimulation. *Review of Physiology, Biochemistry and Pharmacology, 120*, 115-202.

Plisk, S., & Stone, M. H. (2003). Periodization strategies. *Strength and Conditioning Journal, 17*(6), 19-37.

Reiser, R. F. (2006). Building a better understanding of basic mechanical principles through analysis of the vertical jump. *Strength and Conditioning Journal, 28*(4), 70-80.

Ricard, M. D., & Veatch, S. (1990). Comparison of impact forces in high and low impact aerobic dance movements. *International Journal of Sport Biomechanics, 6*(1), 67-77.

Rossi, S. J., Buford, T. W., Smith, D. B., Kennel, R., Haff, E. E., & Haff, G. G. (2007). Bilateral comparison of barbell kinetics and kinematics duing a weightlifting competition. *International Journal of Sports Physiology and Performance, 2*(2), 150-158.

Sacks, R. D., & Roy, R. R. (1982). Architecture of the hind limb of muscle of cats: functional significance. *Journal of Morphology, 1*, 185-195.

Sayers, S. P., Harackiewicz, D. V., Harman, E. A., Frykman, P. N., & Rosenstein, M. T. (1999). Cross-validation of three jump power equations. *Medicine and Science in Sports and Exercise, 31*(4), 572-577.

Schilling, B. K., Stone, M. H., O'Bryant, H. S., Fry, A. C., Coglianese, R. H., & Pierce, K. C. (2002). Snatch technique of collegiate national level weightlifters. *Journal of Strength and Conditioning Research, 16*(4), 551-555.

Schmidtbleicher, D. (1992). Training for power events. In P. V. Komi (Ed.), *Strength and Power in Sport* (pp. 381-395). Oxford: Blackwell Scientific Publications.

Simenz, C. J., Dugan, C. A., & Ebben, W. P. (2005). Strength and conditioning practice of National Basketball Association strength and conditioning coaches. *Journal of Strength and Conditioning Research, 19*(3), 495-504.

Sleivert, G., & Taingahue. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology, 91*, 46-52.

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 early phase of heavy-resistance training in men and women. *Journal of Applied Physiology, 76*(3), 1247-1255.

Stone, M. H. (1993). Literature review: Explosive exercises and training. *National Strength and Conditioning Association Journal, 15*(3), 7-15.

Stone, M. H., Byrd, R., Tew, J., & Wood, M. (1980). Relationship between anaerobic power and Olympic weightlifting performance. *Journal of Sports Medicine, 20*, 99-102.

Stone, M. H., Moir, G., Glaister, M., & Sanders, R. (2002). How much strength is necessary? *Physical Therapy in Sport, 3*, 88-96.

Stone, M. H., O'Bryant, H. S., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003a). Power and maximum strength relationships during performance of dynamic and static weight jumps. *Journal of Strength and Conditioning Research, 17*(1), 140-147.

Stone, M. H., O'Bryant, H. S., Williams, F. E., Johnson, R. L., & Pierce, K. C. (1998). Analysis of bar paths during the snatch in elite male weightlifters. *Strength and Conditioning, 20*(4), 30-38.

Stone, M. H., Sanborn, K., O'Bryant, H. S., Hartman, M., Stone, M. E., Proulx, C., Ward, B., & Hruby, J. (2003b). Maximum strength-power-performance relationships in college throwers. *Journal of Strength and Conditioning Research, 17*(4), 739-745.

Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of error in determining countermovement jump height with the impulse method. *Journal of Applied Biomechanics, 17*, 43-54.

Szymanski, D. (2001). Recommendations for the avoidance of delayed-onset muscle soreness. *Strength and Conditioning Journal, 23*(4), 7-13.

Tricoli, V., Lamas, L., Carnevale, R., & Ugrinowitsch, C. (2005). Short-term effects on lower-body functional power development: Weightlifting vs. vertical jump training programs. *Journal of Strength and Conditioning Research, 19*(2), 433-437.

Viitasalo, J. T., & Komi, P. V. (1978). Force-time characteristics and fiber comparison in human leg extensor muscles. *European Journal of Applied Physiology, 40*, 7-15.

Walshe, A. D., Wilson, G. J., & Ettema, G. J. C. (1998). Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance. *Journal of Applied Physiology, 84*(1), 97-106.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology, 89*(5), 1991-1999.

Wickiewicz, T. L., Roy, R. R., & Powell, P. L. (1984). Muscle architecture and force-velocity retationships in humans. *Journal of Applied Physiology, 57*(2), 435-443.

Wilson, G. J., Lyttle, A. D., Ostrowski, K. J., & 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.

Wilson, G. J., Newton, R. U., Murphy, A. J., & Humphries, B. J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise, 25*(11), 1279-1286.

Winchester, J. B., Erickson, T. M., Blaak, J. B., & McBride, J. M. (2005). Changes in bar-path kinematics and kinetics after power-clean training. *Journal of Strength and Conditioning Research, 19*(1), 177-183.

Winter, D. A. (1992). Kinematics. In D. A. Winter (Ed.), *Biomechanics and Motor Control of Human Movement* (2nd ed.). New York: John Wiley and Sons, Inc.

Wood, G. A. (1982). Data smoothing and differentiation procedures in biomechanics. *Exercise and Sport Sciences Reviews, 10*, 308-362.

Young, W. (1995a). Laboratory strength assessment of athletes. *New Studies in Athletics, 10*(1), 89-96.

Young, W. (1995b). Strength qualities: What they are and what they mean to the coach. *Strength and Conditioning Coach, 3*(4), 13-16.

Young, W. (2006). Transfer of strength and power training to sports performance. *International Journal of Sports Physiology and Performance, 1*, 74-83.

Young, W., Benton, D., Duthie, G., & Pryor, J. (2001a). Resistance training for short sprints and maximum-speed sprints. *Strength and Conditioning Journal, 23*(2), 7-13.

Young, W., & Farrow, D. (2006). A review of agility: Practical applications for strength and conditioning. *Strength and Conditioning Journal, 28*(5), 24-29.

Young, W. B., James, R., & Montogomery, I. (2002). Is muscle power related to running speed with changes of direction? *Journal of Sports Medicine and Physical Fitness, 42*(3), 282-288.

Young, W. B., McDowell, M. H., & Scarlett, B. J. (2001b). Specificity of sprint and agility training methods. *Journal of Strength and Conditioning Research, 15*(3), 315-319.

Young, W. B., Newton, R. U., Doyle, T. L., Chapman, D., Cormack, S., Stewart, G., & Dawson, B. (2005). Physiological and anthropometric characteristics of starters and non-starters and playing positions in elite Australian Rules football: a case study. *Journal of Science and Medicine in Sport, 8*(3), 333-345.

APPENDICES

are not included in this version of the thesis