KINETICS AND KINEMATICS OF
STRENGTH AND POWER DEVELOPMENT

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A THESIS SUBMITTED TO AUT UNIVERSITY

IN FULFILMENT OF THE DEGREE OF

DOCTOR OF PHILOSOPHY

2008

SCHOOL OF SPORT AND RECREATION

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Table of contents

Attestation of authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made.

Nigel Harris
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Date
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Acknowledgements

John Cronin. Thank you so much JC! Your passion for strength and conditioning research and practice is inspirational. Your supervision has extended well beyond the bounds of this PhD into the mentorship of my academic and professional progress over the last seven years.

Will Hopkins. Your relentless pursuit of the truth rather than the convention has shaped my approach to research design, analysis and presentation. I consider myself fortunate to have learned the Hopkins way. Thank you!

Publishing my first peer-reviewed research with Cronin and Hopkins as co-authors has been a privilege. Thank you also to Justin Keogh for input at the early stages of this thesis.

Sue. My long-suffering wife, you are my rock. This PhD has been a journey for both of us and our beautiful kids Nina and Ed. Your belief in me through the downs and ups has been steadfast and utterly crucial to my successful completion.

The School of Sport and Recreation, AUT University. Thank you for providing resources and funding.

My exercise science team colleagues. I value our collegiality. Thanks for the understanding throughout this (long) process.

Subjects. Thanks to the many willing subjects who volunteered. Special thanks to Keir Hansen and the first grade NZ Warriors team of 2004/5 – you were great to deal with.

New Zealand Rugby Football Union. Thank you for contributing to the funding of equipment used in this thesis.

Publications and presentations arising from this PhD thesis

Chapter two of this thesis represents a combination of two separate papers, one of which has been published in a peer-reviewed journal and the other submitted to a peer-reviewed journal for consideration for publication. Chapters three to six represent the papers as printed, in-press or under submission in peer-reviewed journals.

Published (or in-press) peer-reviewed articles

Harris, N. K., Cronin, J. B., and Keogh, J. W. (2007). Contraction force specificity and its relationship to functional performance. Journal of Sports Sciences, 25(2), 201-212.
(Nigel Harris 90%, John Cronin and Justin Keogh 10%)

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2007). Power outputs of a machine squat-jump across a spectrum of loads. Journal of Strength and Conditioning Research, 21(4), 1260-1264.
(Nigel Harris 90%, John Cronin and Will Hopkins 10%)

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2008). Relationship between sprint times and the strength/power outputs of a machine squat-jump. Journal of Strength and Conditioning Research, 22(3), 691-698.
(Nigel Harris 90%, John Cronin and Will Hopkins 10%)

Harris, N. K., Cronin, J. B., Hopkins, W. G., and Hansen, K. T. (2008). Squat-jump training at maximal power: Does it enhance sprint ability? Journal of Strength and Conditioning Research, In press (due for publication mid 2008).
(Nigel Harris 85%, John Cronin and Will Hopkins 10%, Keir Hansen 5%, provided access to athletes for data collection)

Peer-reviewed articles currently under review

Harris, N. K., Cronin, J. B., Hopkins, W. G., and Hansen, K. T. (2008). Inter-relationships between machine squat-jump strength, force, power and 10 m sprint times in trained sportsmen. Journal of Sports Medicine and Physical Fitness, Submitted - in first review.

(Nigel Harris 85%, John Cronin and Will Hopkins 10%, Keir Hansen 5%, provided access to athletes for data collection)

Conference presentations

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2004a). Force-velocity-power profile of a machine jump-squat. Podium presentation at the 4th International Conference on Strength Training. Serres, Greece.
(Nigel Harris 90%, John Cronin and Will Hopkins 10%)

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2004b). Force-velocity-power outputs of fast versus slow sprinters. Poster presentation at the 4th International Conference on Strength Training. Serres, Greece.
(Nigel Harris 90%, John Cronin and Will Hopkins 10%)

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2004c). Force-velocity-power profile of a machine jump-squat. Podium presentation at the New Zealand Sports Medicine and Science Conference, Auckland.
(Nigel Harris 90%, John Cronin and Will Hopkins 10%)

Harris, N.K. (2004) Strength training for sporting performance – where's it at? Podium presentation at the Netfit Convention, Auckland.
(Nigel Harris 100%)

Harris, N.K. (2005) Strength training for sporting performance case studies. Podium presentation at the Netfit Convention, Auckland.
(Nigel Harris 100%)

Harris, N. K. (2005) Strength training for sporting performance – where's it at?
Podium presentation at the Network Fitness Convention, Melbourne, Australia.
(Nigel Harris 100%)

Harris, N. K., Cronin, J. B. (2005). Force-velocity-power outputs of fast versus slow sprinters. Podium presentation at the New Zealand Sports Medicine and Science Conference, Queenstown.
(Nigel Harris 90%, John Cronin 10%)

Harris, N. K. (2006) Strength training for sporting performance – where's it at?
Podium presentation at the FILEX International Fitness Convention, Sydney, Australia.
(Nigel Harris 100%)

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2006). Relationship between kinetic and kinematic outputs of a machine jump squat and sprint times. Paper presented at the New Zealand Sports Medicine and Science Conference, Wellington.
(Nigel Harris 90%, John Cronin and Will Hopkins 10%)

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2007). Squat-jump training at maximal power: Does it improve sprint ability? Paper presented at the New Zealand Sports Medicine and Science Conference, Hamilton.
(Nigel Harris 90%, John Cronin and Will Hopkins 10%)

Harris, N. K., Cronin, J. B., Hopkins, W. G., and Hansen, K.T. (2008). Inter-relationships between machine squat-jump strength, force, power and 10 m sprint times in trained sportsmen. Accepted for podium presentation at The 6th International Conference on Strength Training, Colorado, USA.
(Nigel Harris 85%, John Cronin and Will Hopkins 10%, Keir Hansen 5%, provided access to athletes for data collection)

Non peer-reviewed articles relating to this thesis

Harris, N. (2004) Strength training for sporting performance 1: In support of going ballistic. Netfit 6 (3) October 2004
(Nigel Harris 100%)

Harris, N. (2005a) Strength training for sporting performance 2: Heavy or light – which is best? Netfit 6 (4) December 2004
(Nigel Harris 100%)

Harris, N. (2005b) Strength training for sporting performance 3: Specificity. Netift 7 (1) March 2005.
(Nigel Harris 100%)

Harris, N. (2005c) Strength training for sporting performance 4: Advanced weight training techniques for sport. Netift 7 (2) July 2005.
(Nigel Harris 100%)

Harris, N. (2006). Heavy duty - strength for sport. Fitnesslife, 74-75.
(Nigel Harris 100%)

Harris, N. (2007). Manpower – power training. Fitnesslife, 30, 52-54.
(Nigel Harris 100%)

List of tables

List of figures

ABSTRACT

The use of the squat exercise (and its derivatives) in gym-based settings is widespread owing to perceived functional performance enhancing effects. In particular, there has been a preponderance amongst practitioners with loads that maximise power outputs (Pmax) based on a perception that mechanical peak power is directly related to explosive functional performance such as sprinting ability. The optimal muscular quality associated with squats remains elusive though, mostly due to methodological limitations in the research. The four experimental studies in this thesis sought to quantify the kinetic and kinematic outputs of a machine squat-jump and their relationship to sprinting ability, both descriptively and across a training period. First, an analysis of the kinetic and kinematic outputs of a machine squat-jump across a spectrum of loads was performed, with an emphasis on power output. Then, the relationship of these outputs with sprint ability was investigated. Correlations do not imply cause and effect, thus a training intervention was undertaken to quantify the relationships of the change in performance measures over time, and allow a comparison of different training protocols. Specifically, one training group was prescribed training loads based on individually determined peak power outputs, and the other based on traditional maximal strength training loads. Because the intention of this thesis was to enhance our knowledge of best strength training practice for elite sporting performance, highly trained athletes were specifically chosen as subjects, cognizant of the population specific nature of training adaptation.

In study one, it was determined that the point on the power-load spectrum where peak and mean power occurred in the machine squat-jump was 21.6 ± 7.1 %1RM (mean $\pm$ SD) and 39.0 ± 8.6 %1RM respectively although there was considerable individual variation in these points. A broad plateau in power outputs was evident for most subjects with at most a 9.9% (90% confidence limits ±2.4%) difference in peak or mean power at loads up to 20 %1RM either side of the peak. Studies two and three established that, of the multiple kinetic and kinematic measures investigated, only 1RM strength, work and impulse (all relative to body mass) provided any indication of useful kinetic / kinematic outputs that were potentially worthwhile developing for enhancing sprint performance, albeit with only moderate correlations ($r = \sim$ -0.3). Additionally, the intercorrelations between maximal strength and explosive kinetic and kinematic measures were only moderate ($r = \sim$0.3), casting doubt on the common practice of

pursuing high 1RM strength with the intention of improving explosive muscle performance. The training study provided evidence that training at the load that maximised individual peak power output was no more effective for improving sprint ability than training at heavy loads and the changes in kinetic and kinematic outputs were not usefully related to changes in sprint ability.

Thesis rationale

Professional strength and conditioning trainers and sports scientists continually strive to incorporate the best evidence-based practice within the training programmes they provide. It is patently manifest though that some common practices are based largely on anecdotal evidence and unsound or outdated research findings. For example, many strength and conditioning trainers seem to focus on constantly increasing maximal strength based on an assumption that 'stronger' means 'faster and higher', despite a paucity of supporting evidence. Additionally there has been a recent increase in the popularity of training at so-called 'Pmax', the point on the load spectrum where peak power output is maximised for a particular exercise. It is not uncommon to see strength and conditioning personnel and sport scientists alike instrument certain machines with the intention of quantifying Pmax in testing and training. But, is Pmax actually related to functional performance? Is training at peak Pmax load superior to training at other loads? Are there other kinetic and kinematic measures that may be of more use to improving functional sporting performance than simple measures of strength or peak power? The literature is certainly equivocal in these areas.

Functional performance is very sports specific, but common to many sports is the requirement to sprint fast, particularly over shorter distances (Cronin and Hansen, 2005). Hence, 10- to 40-m sprint performance was chosen as the functional performance measure of interest in this thesis. There is considerable research investigating the relative efficacy on sprint performance of one gym-based loading scheme over another (Adams, O'Shea, O'Shea, and Climstein, 1992; Blazevich and Jenkins, 2002; Harris, Stone, O'Bryant, Proulx, and Johnson, 2000; Kotzamanidis, Chatzopoulos, Michailidis, Papaiakovou, and Patikas, 2005; Lyttle, Wilson, and Ostrowski, 1996; McBride, Triplett-McBride, Davie, and Newton, 2002; Tricoli, Lamas, Carnevale, and Ugrinowitsch, 2005; Wilson, Newton, Murphy, and Humphries, 1993). Generally, studies in this area are typified by considerable methodological limitations thus confounding our understanding and limiting our ability to draw conclusions. These include the type of dynamometry used in testing, the training experience of research subjects, the specific technique employed in a lift, the equation of training volume and the methods of collection and calculation. The squat exercise

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and its derivatives such as squat-jumps typically form the basis of most lower body strength programmes despite being biomechanically dissimilar to sprinting (Mann and Sprague, 1980; Zafeiridis et al., 2005). Hence, this thesis sought to closely examine the kinetic and kinematic measures of a machine squat-jump across a range of loads, establish how they were related to sprint performance, and quantify whether training at Pmax was indeed a superior approach for the enhancement of sprint performance thus providing clearer insight into best strength training practice.

Originality of the thesis

- Currently there is limited and contradictory research on the kinetics and kinematics associated with squat-jumps across a full spectrum of loads in well-trained athletes.
- Research seeking to quantify the difference in power outputs of loads either side of peak power output load is very limited.
- No study has investigated the relationship between sprint ability in well-trained athletes and the kinetic / kinematic outputs of a machine squat-jump across a range of loads.
- No study has examined the inter-relationships between maximal strength and a full range explosive kinetic and kinematic measures at different loads.
- No study has specifically identified peak power outputs for each individual on the specific isoinertial resistance training exercise used in both testing and training and compared it to an alternative training group(s). No study has tracked strength, force and power outputs on that exercise, and related these changes to change in sprint ability over a training period.

Thesis organisation

This thesis consists of seven chapters. Chapter two is a review of the literature. It first overviews the methodological issues confounding current understanding in this area, then reviews research seeking to quantify the relationships between strength, kinetic and kinematic outputs and sprint ability. Subsequently, it reviews training studies that have tracked both change in power measures and change in sprint performance. Chapters three, four, five and six are the experimental studies presented in the format of the journals for which they were written, with the exception that each is preceded by a brief

explanatory prelude rather than an abstract (instead, the abstracts are included in appendix four). Consequently, there is some repetition between the review and experimental chapters. The final chapter consists of general conclusions and recommendations for strength and conditioning practitioners. References are included at the end of each chapter and an overall reference list from the entire thesis has been collated at the end of the final chapter. For consistency, all referencing is in APA format.

The appendices present relevant peripheral material including informed consent form, ethics approval and subject information sheets.

CHAPTER 2. LITERATURE REVIEW

Introduction

Strength and power are thought critical to the performance of many athletic tasks (Stone, Moir, Glaister, and Sanders, 2002). Consequently best practice for improving functional performance through resistance strength training (RST) has been the subject of much research and subsequent conjecture. Research that has investigated strength, power and functional performance has been typified by a considerable variation in the methods used. The scope of this variation makes comparisons difficult and hence definitive conclusions problematic. Some of the conjecture can be attributed to the multi-factorial nature of strength and power. For example, strength has been generally defined as the peak force developed in a maximal voluntary isometric contraction (MVIC) or as the maximum load that can be lifted for one repetition (1RM). Power is defined as the rate at which mechanical work is performed or as the product of force and velocity (Abernethy, Wilson, and Logan, 1995; Harman, 1993; Sale, 1991a). However, other definitions acknowledge the specificity of strength and power, in that their expression is affected by body position, movement pattern, velocity, contraction type and contraction force (Sale, 1991a). That is, strength and/or power exhibited under one set of conditions could be quite different under another (Atha, 1981).

A commonly prescribed and researched exercise used in gym-based settings is the squat and its derivatives such as the squat-jump. This review first addresses the methodological issues concerning our interpretation of the results in an attempt to clarify the strength and power qualities of the squat and squat derivatives that may be worthwhile developing in the pursuit of improved sprint ability. The discussion provides the delimitations for analysis of research into the relationships of strength and power with sprint ability and, subsequently, training studies that have investigated change in power and sprint measures. Finally, recommendations are formulated with the aim to assist assessment and training practice as well as provide direction for future research.

Training status of study subjects

The training status of the study subjects is an important methodological issue to consider when attempting to generalise practical applications from study findings of one specific group to another. For example, a widely quoted review of strength training research is that by McDonagh and Davies (1984). These authors reviewed research from 1949 to 1983 and based their findings largely on studies involving novice subjects. Strength increases were presented as percent change in MVIC per day, load was expressed as %1RM (converted with the authors empirically designed formulae where required) and the duration of each contraction was listed in seconds. The key result of the review was that 66 %1RM was the critical threshold for the development of isometric and isotonic strength. This review became central to many assertions about the optimal load for the development of strength. However, it is problematic to extrapolate findings from novice weight training subjects to more experienced weight trainers. Indeed it has been suggested that initial strength increases for novices will occur rapidly as a result of almost any resistance training method (Chestnut and Docherty, 1999; Wilson, 1993).

There are a preponderance of training studies that have used novice weight trainers as subjects to compare the effects of different training protocols on strength, power, functional performance and/or changes in muscle cross-sectional area (CSA). Most of these studies have found little difference in the magnitude of the adaptations resulting from the different training protocols (see Table 2.1). For example, Chestnut and Docherty (1999) used two groups of novice weight trainers. One performed eight sets of four repetitions at 4RM (~85%1RM) of various triceps and bicep exercises and the other performed four sets of ten repetitions with 10RM (~70%1RM) of the same exercises. Measurements before, during and after the 10-week training period included triceps bench press and standing bicep curl 1RM, and mid upper arm CSA. Both groups demonstrated significant increases in forearm extensor and flexor 1RM and upper arm CSA, with no significant difference in the rate of improvement between groups. Chestnut and Docherty (1999) suggested that the inexperience of the subjects was responsible for the 'generic' training response between the groups and that a more experienced subject group would have responded differently to the same training.

Table 2.1. The effect of training status on resistance-training induced changes in strength and power

Study	Frequency	Duration	Sets x Reps	Load	Training	Volume equation	% Change in Strength
Novice Subjects							
Chestnut & Docherty (1999)	3 x week	10 weeks	8 x 4 / 4 x 10	85%1RM / 70% 1RM	Isoinertial	Sets x reps x load	15% / 6%[1]* / 17% / 9.5%*
Dons et al. (1979)	3 x week	7 weeks	1 x 20 / 1 x 12	50% 1RM / 80% 1RM	Isoinertial	Sets x reps x load	23.8%* / 42.3%*
Hakkinen & Komi (1981)	3 x week	12 weeks	1-6 reps / set	80-100%1RM	Isoinertial	Not stated	20.3%*
Hisaeda et al. (1996)	3 x week	8 weeks	5 x 15-20 / 8 x 4-5	15-20RM / 4-5RM	Isoinertial	No	20.3%[2]* / 32.5%*
Lyttle et al. (1996)	2 x week	8 weeks	2-6 x 8 / 1-3 x 6-10	30%1RM / 6-10RM	Ballistic Combined	Sets x reps x load	14.7%* / 14.8%*
Thorstensson et al. (1976)	3 x week	8 weeks	9 x 6	78% 1RM	Isoinertial + jumps	No	73%*
Young & Bilby (1993)	3 x week	7 ½ weeks	4 x 8-12 / 4 x 8-12	8-12RM / 8-12RM	Slow Fast	No	21.7%* / 20.1%*
Experienced Subjects							
Baker (2001)	2 x week	29 weeks					N/C
	2 x week	19 weeks	Not stated	Not stated	Not stated		4.9%
Hakkinen & Komi (1981)	3 x week	12 weeks	1-6 reps / set	70-100%1RM	Olympic lifts	Not stated	6.4%
Hakkinen et al. (1987)		1 year	Not stated	Mean 78%1RM	Olympic lifts	Not stated	1.7%

Moss et al. (1997)	3 x week	9 weeks	3-5 x 2	90%1RM			15.2%*
			3-5 x 7	35%1RM		Contractile time	10.1%*
			3-5 x 10	15%1RM			6.6%*
Wilson et al. (1993)	2 x week	10 weeks	3-6 x 6-10	6-10RM	Slow		8.7%[3]*
			3-6 x 6-10	Bodyweight	Explosive	No	1.3%
			3-6 x 6-10	30% MVIC	Explosive		7.0%*

[1] (pre-mid / mid-post)
[2] Average peak torque
[3] Peak isokinetic torque
*Significant at ≤0.05

In contrast to the studies using novice subjects, studies that have used more experienced weight trainers have tended to find much smaller gains in performance even with more prolonged training programs. Hakkinen et al. (1987) examined changes in MVIC and 1RM over a one year training period in elite competitive weightlifters. Individual coaches set the programmes for each athlete, therefore training diaries were kept for the year to quantify the training performed. Although no specific details of training were given, exercises consisted predominantly of dynamic Olympic style lifts at a mean load of ~78% 1RM (with some small variations throughout the year). Over the course of the study, changes in MVIC and 1RM were reported to be small and insignificant (3.5 and 1.7% respectively). Hakkinen et al. (1987) suggested that the magnitude of the neuromuscular adaptations during strength training in elite strength athletes differed from those reported for previously untrained subjects. Similar reports of little change in performance from resistance training in experienced resistance-trained athletes have been reported in several studies. For example, Baker (2001c) studied the strength and power changes in a group of elite national rugby league (NRL) and college-aged (SRL) standard rugby league players over the course of a season (29 and 19 weeks respectively). Although not stated explicitly, these athletes would have had a resistance training background, as indicated by their 1RM bench press scores (NRL 137.9 ± 13.3 kg and SRL 110.3 ± 17.0 kg). Training over the course of the study consisted of twice weekly whole-body resistance training sessions, two to three 20-30 minute high intensity conditioning sessions, three to five team practice sessions (which typically involved an inherently high degree of energy system conditioning) and, although not stated, presumably one game per week as well. Training was periodised for volume and intensity over the course of the season. Tests were conducted at the start of the season, one to two times periodically through the season, and at the conclusion of the season. These tests included 1RM bench press, maximum power output during bench press throws of 40, 50, 60, 70, and 80 kg, and maximum power output during jump squats at loads of 40, 60, 80 and 100 kg. For the NRL group, no significant change was observed for any of the variables tested. The SRL group significantly increased their 1RM strength in the bench press (4.9%) from the pre-season test to the week nine testing occasion. It then remained unchanged until the week 19 test. No other variable changed significantly over the course of the season for the SRL group. It was suggested that the magnitude of resistance-training gains are dependent on training experience,

with the greater strength training experience of the NRL group reducing the scope for strength improvements compared to the SRL players.

There is also some evidence suggesting that subjects with greater strength training and/or athletic experience produce different magnitude of power outputs across the load spectrum, and different load/power curve characteristics than their less experienced counterparts (Baker, 2001a; Stone, O'Bryant et al., 2003). For example, stronger athletes tend to produce their highest power outputs at a lower %1RM than their weaker counterparts in both upper (Baker, 2001b; Newton, Murphy, Humphries, Kraemer, and Hakkinen, 1997) and lower body (Baker, 2001a; Baker, Nance, and Moore, 2001; Sleivert and Taingahue, 2004; Stone, Sanborn et al., 2003) exercises. Thus, generalising findings from novice subjects to athletes with experience in weight training would seem invalid.

Power measurement techniques

Data collection and analysis equipment clearly impacts on power output in both upper and lower body movements (Cormie, McBride, and McCaulley, 2007b; Cronin and Henderson, 2004; Cronin, Hing, and McNair, 2004). Commonly used equipment for collection of kinematic and kinetic data during weight lifting movements include linear position transducers, rotary encoders, and videography, each characterised by its own limitations. Force platforms are used to measure ground reaction forces, either exclusively or in conjunction with one of the devices listed above. Devices such as linear position transducers are most useful for accurate measurement of bar displacement and time, therefore velocity and acceleration may be indirectly assessed. Force and power must be derived from calculations based on inclusion of mass into the equation. Inherently then, any noise associated with the displacement-time signal may be amplified during calculations, increasing the potential for error. The use of a single linear position transducer is also considered to be of limited validity for collection of displacement-time data in some free-weight exercises due to their inability to ascertain both horizontal and vertical displacement. In such cases it has been recommended that two transducers be used in a triangular formation with the bar (Cormie, Deane, and McBride, 2007). Force platforms rely on inverse dynamics (impulse-momentum approach) from ground reaction forces and so are also prone to magnification of data collection noise for extrapolation of power outputs. Additionally, they do not account

for barbell movement independently of the body, so velocity may be underestimated (Hori, Newton, Nosaka, and McGuigan, 2006). Given that both position transducers and force platforms each have their own limitations, Cormie et al. (2007b) proposed that a superior approach to data collection would involve both pieces of equipment. Nonetheless, for exercises where movement is restricted to one plane of motion such as a Smith-machine squat it may be argued that a position transducer alone allows for reasonably accurate data to be collected. The affordability, portability and accessibility of a transducer over force plates also provides a justification for their widespread use in a training and testing setting.

Power calculation and expression

Mechanical power output has attracted a great deal of attention in the research and conditioning fraternity particularly in terms of it's relationship to functional performance (Baker and Nance, 1999a, 1999b; Kukolj, Ropret, Ugarkovic, and Jaric, 1999; Meckel, Atterbom, Grodjinovsky, Ben-Sira, and Rotstein, 1995; Sleivert et al., 2004; Thomas, Fiatarone, and Fielding, 1996; Young, McLean, and Ardagna, 1995; Young, James, and Montgomery, 2002). However, disentangling the effects of increasing power output on improvements in functional performance is challenging due to discrepancies in terminologies and methods for the calculation of power output. The term 'peak power' has been ambiguously reported or misrepresented. For example, it is sometimes unclear whether or not the term peak power refers to peak average power output or peak maximal power output (Baker et al., 1999b; Hammett and Hey, 2003). Power output (W) has also been calculated from jump height and body mass. Harris et al. (2000) for example, used the equation of Harman et al. (1991) to estimate peak maximal power from counter-movement vertical height: 61.9 X jump height (cm) + 36.0 X body mass (kg) – 1822. Hammett and Hey (2003) also calculated power from vertical jump height using the formula: 2.21 X body mass (kg) X $\sqrt{}$ jump height distance (m). The authors do not specify the unit of measurement and the reported means for power are incongruous with the typical power outputs (peak and mean, absolute and relative to body mass) reported in other research. A multitude of other strength qualities have also been represented as power. For example, rate of force development, starting strength and isometric rate of force development have been termed power, but are representative of strength qualities quite distinct from mechanical power output (Enoka, 2002). Accurate and standardised calculation and reporting of power is of utmost importance if useful interpretation of research in this area is to be made.

System mass

In lower body movements such as the squat-jump the inclusion or exclusion of body mass in the equation of power is considered an important and influential methodological issue (Cormie, McBride, and McCaulley, 2007a; Cronin and Sleivert, 2005; Dugan, Doyle, Humphries, Hasson, and Newton, 2004; Hori et al., 2006). Although conjecture exists (Sleivert et al., 2004), it is generally thought appropriate to use system mass (inclusion of body mass) to calculate force and power outputs during squat-jumps because the subject must propel themselves and the mass associated with the bar. Excluding body mass decreases the total mass component of force therefore decreasing total power output. Consequently, the point on the load spectrum where peak power output occurs will substantially shift toward the heavier loads and a proportionately larger error in calculation of power at lighter loads will occur (Dugan et al., 2004). Some authors (Cormie, McBride et al., 2007a, 2007b) have suggested that the mass of the lower legs and feet (shank mass; ~ 12% of body mass) should be excluded from the force and power equations because technically they remain relatively static during the concentric phase of a squat jump prior to take off, where peak power typically occurs. Dugan et al. (2004) though, postulated that inclusion or exclusion of shank mass will not have a large impact on the shape of the load-power curve. It appears the general consensus is that body mass should be included in force and power equations for ballistic lower body movements such as squat-jumps, but excluded when the movement of the mass is largely independent from the movement of the body such as in some Olympic style derivative lifts. For typical upper body movements such as the bench press only a fraction of body mass is propelled hence inclusion or exclusion of any body mass is considered practically inconsequential.

Kinetics and kinematics

It is generally accepted that maximal or near maximal forces are required to recruit and overload the higher threshold type II fibres and that heavy loads (~60 %1RM and above) are necessary to achieve this (Bloomer and Ives, 2000; McDonagh et al., 1984; Sale, 1992). However, most studies have reported only the load used during training and/or testing and not the forces associated with the use of these loads. By definition, force is the product of mass and acceleration. Therefore, determining the acceleration profile of a lift is important, in that higher forces can result from greater accelerations as

well as an increase in load. Consequently, if a given submaximal load is moved with maximal acceleration, it could impose a different stress on the neuromuscular system and hence result in different adaptations. Figure 2.1 illustrates the interrelation between muscle force, velocity and power.

Figure 2.1. Interrelation between muscle force, velocity and power.

Adapted from Toji & Kaneko (2004).

In traditional weight training lifts where the bar and/or load reaches a velocity of zero at the end of the concentric phase, deceleration occurs for a considerable portion of the contraction (Baker et al., 2001; Wilson, 1993). For example, loads of 81 %1RM resulted in deceleration for 51.7% of the concentric phase during a bench press where the grasp was maintained on the bar at the end of the concentric phase (Elliott, Wilson, and Kerr, 1989). An alternative technique where the load (bar and/or oneself) is projected as in jumping and throwing has been termed 'ballistic' training and can result in higher force outputs (Newton and Kraemer, 1994). The following briefly reviews the kinematics and kinetics of both traditional and ballistic techniques for lower body exercises.

Baker et al. (2001) examined the power outputs during jump squats across a range of loads in power-trained athletes. Maximum strength (1RM) was assessed using a full-squat exercise and power output was assessed across loads of 40, 60, 80, 100, and 120 kg. These absolute loads represented an equivalent load of approximately 25, 38, 51, 64, and 75% of 1RM respectively (mean across study groups). To analyse power outputs the barbell mass was added to the body mass of the athlete so power output was related to the total system-mass. Using the system-mass, the mean mechanical power output for the concentric flight phase of the jump-squat at each load was determined. Subjects performed countermovement jumps to a self-selected depth. Mean power output (1772 W) was maximised at loads representing 55-59% of the 1RM full squat strength, although it was noted that loads representing the range of 47-63% also produced similar power outputs. In contrast to the ballistic squat technique used in the study above, studies using traditional squatting techniques such as the half squat have reported much lower maximum power outputs. For example, Izquierdo et al. (2002) investigated power output across loads of 30, 40, 50, 60, 70, 80, 90 and 100 %1RM in several groups of athletes. Maximum power output occurred between 45 and 60% and was reported to be 385 – 755 W. This is considerably lower than other studies using ballistic techniques. Cormie et al. (2007) directly compared the squat, jump-squat and power clean for power outputs across a spectrum of loads in division I male athletes (football players, sprinters, long jumpers). Peak power output was optimised at 56 (~3300 W extrapolated from graph), 0 (no external load) (~6200 W) and 80 %1RM (~4800 W) for the squat, jump-squat, and power clean respectively, clearly highlighting the differences in power-load characteristics of each exercise.

It appears from the literature reviewed that due to the ability to accelerate a load through the entire concentric phase, ballistic techniques produce superior force, velocity and power outputs to traditional training techniques. However, there is very limited literature that has investigated the force-velocity-power profile of lower body ballistic techniques (e.g. squat-jump) across the load continuum. Determining the force-velocity-power profiles of the lower body as a function of system-mass is required, as much of the literature has failed to calculate the kinetic variables of interest in such a manner. If such profiles are related to functional performance measures our understanding of assessment and conditioning practice should be improved. Furthermore, given the clear differences in kinetic and kinematic outputs between

ballistic and traditional lifts, it would appear that specifying the exact type of movement used in studies is of great importance.

Set kinetics and kinematics

Although a greater understanding of single repetitions is required, strength and power training is characterised by multiple repetitions and sets. When set characteristics are investigated as opposed to single repetitions, further insight into the acute stresses imposed on the body by various resistance training techniques or loading schemes is gained. Cronin and Crewther (2004) investigated the temporal, kinematic and kinetic characteristics of three equi-volume training loads of experienced weight trainers. Three sets were tested at different loads (30, 60 and 90 %1RM) and each set was equated by volume (reps x load) to ensure total load lifted was identical. Testing was conducted using a 'ballistic squat' where subjects were instructed to jump with maximal intensity. It was reported that a single repetition at 90 %1RM produced greater mean and peak forces and time under tension than a single repetition at the lighter loads, but when equated by volume the 30 %1RM condition produced significantly greater time under tension, peak and total power outputs. These findings draw attention to the importance of considering the kinetics and kinematics over a set, as opposed to a single repetition.

As evidenced by the paucity of literature in this area, there is a great need for this type of research. Furthermore, realisation that adaptation of muscle depends on some interaction between mechanical, hormonal and metabolic responses (Enoka, 2002), gaining an understanding of these responses during typical strength and power training sessions would develop greater understanding and enhance training prescription. Such an approach will provide a framework for a greater insight into the adaptations associated with longitudinal training studies.

Assessment mode

Many of the discrepancies found in the strength literature can be attributed to the different types of dynamometry used to assess strength and power. Three modes of dynamometry are generally used: isometric (constant angle); isokinetic (constant velocity); and, isoinertial (constant gravitational load) which is also referred to as

isotonic (Abernethy et al., 1995). For a full treatise of the issues and controversies surrounding these three modes of dynamometry, the reader is directed to specific reviews on this topic (Abernethy et al., 1995; Atha, 1981; Sale, 1991a). One issue of interest however, is that the magnitude of the strength/power gains are probably dependent on the assessment mode being similar to the training mode (Morrissey, Harman, and Johnson, 1995). For example, Dons et al. (1979) used both isometric and isoinertial testing to measure the changes in maximal strength of three groups (control, 50 and 80 %1RM training groups). After seven weeks of training, the 80 %1RM group significantly increased 1RM (42.3%) but did not demonstrate a significant increase (4%) in maximum voluntary isometric contraction (MVIC). Dons et al. (1979) commented that their results confirmed specificity of training in that dynamic training did not affect static performance. Using similar methods, Jones and Rutherford (1987) studied the response of the quadriceps to different training regimes. One group performed unilateral isometric training at 80% MVIC. Each repetition was held for four seconds separated by a two second rest period but the number of repetitions was not stated. Another group performed six repetitions at 6RM (80 %1RM) training one leg with concentric contractions and the other with eccentric contractions. Tests before and after the 12-week programme included MVIC assessment, which increased significantly more in the isometric training group (35.0 ± 19.0%) as opposed to the concentric and eccentric training groups (15.0 ± 8.0% and 11.0 ± 3.6% respectively). Thus, it appeared that the greatest change in muscle strength was again found when the mode of training matched that of testing. Similar results (see Table 2.2) have also been reported in several other studies (Hakkinen and Komi, 1986; Wilson, 1993). This specificity of assessment has been proposed to be a result of the mechanical and neural activation differences between isometric and dynamic contractions (Nakazawa, Kawakami, Fukunaga, Yano, and Miyashita, 1991; Ter Haar Romeny, Denier van der Gon, and Gielen, 1982). It seems imprudent to utilise isometric testing to measure dynamic performance and vice versa.

Table 2.2. The effect of assessment mode on strength gains

Study	Frequency	Duration	Sets x Reps	Load	Volume equation	% Change MVIC	% Change 1RM
Isometric Training							
Amusa and Obajuluwa (1991)	3 x week	10 weeks	3 x 6 sec	50-100% of max load that could be held for 6 s	No	83%*	65.8%*
Jones and Rutherford (1987)	3 x week	12 weeks	4 sec	80% MVIC	No	35.0%*	n/a
Dynamic Training							
Dons et al. (1979)	3 x week	7 weeks	1 x 20 1 x 12	50% 1RM 80% 1RM	Sets x reps x load	4.5% 4.0%	23.8%* 42.3%*
Hakkinen and Komi (1981)	3 x week	12 weeks	1-6 reps / set	80-100%1RM 80-130%1RM 80-130%1RM	Not stated	2.4% 16.0%* 12.5%*	20.3%* 29.2%* 28.6%*
Jones and Rutherford (1987)	3 x week	12 weeks	4 x 6 4 x 6	80% 1RM (concentric) 80% 1RM (eccentric)	No	15.0%* 11.0%*	n/a
Thorstensson et al. (1976)	3 x week	8 weeks	9 x 6	78% 1RM	No	16-30%*	73%*
Voigt and Klausen (1990)	3 x week	16 weeks	3 x 6	6RM	No	N/C	27.3%*

* Denotes significance at ≤0.05

It seems that dynamic performance should be assessed via dynamic (i.e. isoinertial and/or isokinetic) contractions. To date, the relative effectiveness of isokinetic and isoinertial dynamometry to monitor the changes in strength and power resulting from dynamic training methods is not clear. This could be due to few studies in this area. Murphy and Wilson (1997) examined the ability of isokinetic and isoinertial tests to reflect training-induced changes in performance. Testing consisted of a squat-jump using an absolute load of 10 kg, an eccentric squat movement loaded at 200% of body mass, peak torque during an isokinetic knee extension movement at two speeds (1.05 and 4.7 rads·s^{-1}), power output during a 6 s cycle test, sprinting speed over 40 m and a 1RM squat. It is not clear whether or not all subjects were experienced weight trainers although it is stated that all were involved in a variety of recreational activities, including weight training. Training consisted of four to six sets of the squat exercise at a load of 6-10RM, performed twice weekly for a period of eight weeks. The only strength measure to change significantly over the training period was the 1RM squat (20.9%). This result is not unexpected given that heavy squats were used in training. The only other variable to change significantly was sprint time, which was reduced by 2.2%. The increase in 1RM was the only measure of muscular performance to be significantly related to the improvement in sprint performance (r = -0.41). Thus, the isoinertial 1RM measure was more associated to change in performance than the isokinetic tests. Several other studies have found similar findings (Abernethy and Jurimae, 1996; Elliott, Sale, and Cable, 2002; Jurimae, Abernethy, Quigley, Blake, and McEniery, 1997; Newton and Waddell, 1993).

Despite the popularity of isometric and isokinetic tests in research, it seems that they are inferior to isoinertial measures in tracking dynamic athletic performance change. This is thought to be a result of the large neural and mechanical differences between isometric and isokinetic tests to functional movements such as running and jumping (Abernethy et al., 1995; Wilson and Murphy, 1996a). Even though isokinetic contractions are dynamic in nature, isokinetic dynamometry involves the measurement of force/torque and or power through a range of motion with the movement performed at constant angular velocity. However, human movement is typified by changing velocities and accelerations. Furthermore the inability of many isokinetic dynamometers to assess stretch-shorten cycle (SSC) activity further detracts from the validity of such an approach, although more recent isokinetic dynamometers do allow SSC contractions to be assessed (Wilson, Walshe, and Fisher, 1997). In terms of

assessment velocity, a great deal of research has used velocities that are disparate to the actual movement velocities of activities such as sprinting and jumping. Further compromising the validity of isokinetic dynamometry is that these assessments are predominantly performed in a non-specific posture (seated) and involve knee flexion/extension type movements. Therefore the motion tends to be uniarticular and open chain in nature. Finally, joint range of motion during assessment typically differs to those found during tasks such as sprinting and jumping. Therefore, the external validity of isokinetic testing is questionable, particularly when compared to isoinertial assessment. Isoinertial dynamometry is the mode of choice for the training and assessment of strength and power, as it allows the closest replication to typical movement patterns and hence has greater face validity than the other contraction modes. Isokinetic dynamometers are also typically expensive and therefore not an accessible testing option in most practical settings. Hence, subsequent reviews of correlational and training research will focus on isoinertial strength and power measures.

Assessment of straight sprint ability

Reliability and accuracy associated with different speed measurement protocols should be considered when interpreting results of studies investigating sprint performance. Some studies have not detailed the procedure used for sprint assessment (Hammett et al., 2003; Lyttle et al., 1996; McBride et al., 2002). Some have utilised electronic timing systems (Coutts, Murphy, and Dascombe, 2004; Deane, Chow, Tillman, and Fournier, 2005; Kotzamanidis et al., 2005; Kraemer, Ratamess, Volek, Mazzetti, and Gomez, 2000; Lyttle et al., 1996; McBride et al., 2002; Murphy et al., 1997; Tricoli et al., 2005) and some have used hand-held stopwatches as the sole means of recording sprint performance (Harris et al., 2000; Hoffman, Fry, Howard, Maresh, and Kraemer, 1991; Wilson et al., 1993). Electronic timing lights are generally considered to be the most reliable and accurate option for recording speed, although the number of light beams (e.g. single or dual beam), starting stance, first step strategy, distance behind the initial timing light and height of the beams all influence the accuracy and repeatability of measurements (Cronin and Templeton, 2006; Duthie, Pyne, Ross, Livingstone, and Hooper, 2006). Furthermore, Cronin et al. (2007) asserted that the use of average speed or time based on a number of trials more reliably maps changes in acceleration and speed performance, although it is common practice to use the best of several recorded trials (Coutts et al., 2004; Deane et al., 2005; Harris et al., 2000; Hoffman, Cooper,

Wendell, and Kang, 2004; Hoffman et al., 1991; Kotzamanidis et al., 2005; Kraemer et al., 2000).

In summary, several important methodological issues should be considered when interpreting research in this area. First, isoinertial dynamometry clearly provides greater face validity for the assessment and development of strength and power for the functional performance movements implicit in most sports. Irrespective of the type of dynamometry used, strength and power gains are quite specific to the testing mode, so it is important that testing mode is closely matched to training and the athletic task of interest. Second, if the intention of research is contributing to the enhancement of sporting performance of top-level athletes then the choice of study subjects is critical. The validity of generalising findings from subjects with little or no training experience (novices) or non-athletes to well-trained athletes is extremely problematic. Third, the specific kinetic and kinematic characteristics of exercises used in testing and training should be detailed. Fourth, the methods of collection and calculation of power measures influence final outputs. In terms of calculating force outputs, body mass should be added to the load mass for so-called ballistic lower body movements such as squat-jumps.

Correlation of strength and power with sprint ability

Of particular interest to many practitioners and researchers is identifying if strength and power outputs (e.g. one repetition maximum, peak power, mean force, etc.) using gym-based resistance strength training exercises such as the squat-jump are related to sprinting ability. Such investigations may provide greater insight into those exercises or variables that offer a superior training stimulus in terms of transference of gym-based gains to improving sprint ability. One approach to answering this question is to use correlational analysis, and many researchers have adopted such an approach (Alexander, 1989; Baker et al., 1999a; Chelly and Denis, 2001; Cronin and Hansen, 2005; Farrar and Thorland, 1987; Hennessy and Kilty, 2001; Kukolj et al., 1999; Wisloff, Castagna, Helgerud, Jones, and Hoff, 2004; Young et al., 1995; Young et al., 2002). In this next section, the correlational research in this area is critiqued with the intention of providing a clearer insight into the relationship between strength/power measures and speed. Medline, SPORT Discus, and Google Scholar databases, years 1960 – 2008 were searched for the following keywords and combinations: sprint; speed; strength; power;

relationship and correlation. Only studies investigating lower-body isoinertial strength and power measures, and sprint performance were included with an emphasis on studies investigating the commonly prescribed squat and squat derivative exercises. A total of 421 subjects were used in the research cited in Table 2.3 of which 55 were females. In terms of age most subjects were in their twenties, although some studies used college aged subjects. Most subjects were involved in sport at college to elite level and most had some strength training background. The results of the following analysis are most relevant to this demographic.

To express a qualitative inference of the magnitude of correlations in subsequent discussion the following scale was used: trivial (0.0-0.1); low (0.1-0.3); moderate (0.3-0.5); high (strong) (0.5-0.7); very high (very strong) (0.7-0.9); or practically perfect (0.9-1.0) (Cohen, 1988; Hopkins, 2002). The key findings are presented in Table 2.3.

Table 2.3. Relationship between sprint performance and isoinertial tests of strength and power

Study	Subjects^	Sprint performance measure	Strength measure	Pearson Correlation Coefficient	Power measure	Syst. Mass	Pearson Correlation Coefficient
Anderson et al. (1991)	39 University athletes	40 yd time	1RM knee extension peak force	0.43*			
Baker & Nance (1999a)	20 professional rugby league players	10 m time	3RM squat 3RM squat / kg body mass	-0.06 -0.39*	Jump-squat mean power (W) Jump-squat mean power (W / kg)	N	-0.02 to -0.08 -0.52 to -0.61*
		40 m time	3RM squat 3RM squat / kg body mass	-0.19 -0.66*	Jump-squat mean power (W) Jump-squat mean power (W / kg) (at loads of 40, 60, 80 and 100 kg)		-0.02 to -0.17 -0.52 to -0.76*
Chelly & Dennis (2001)	11 college handball players	Maximal track running velocity			Average leg hopping power per kg of body mass from continuous jumping protocol according to Bosco (1983) Average treadmill running power (W / kg) Average treadmill power (W)	n/a	0.66* 0.20 0.73*
Costill et al. (1968)	76 physical conditioning students (of which 65 were football athletes)	40 yd time	Squat 1RM	0.20	Unload vertical jump (VJ) height (inches) Unloaded standing broad jump (SBJ) distance (inches)	n/a	-0.62* for both jumps

Cronin & Hansen (2005)	26 professional rugby league players	5 m time 10 m time 30 m time	3RM parallel squat	-0.05 -0.01 -0.29	Jump-squat (30kg) average power (W)	Y	-0.13 -0.11 0.15
Hasegawa (2004)	22 college football players	10 yd time 40 yd time	1RM squat / kg body mass	0.58* 0.57*	Jump-squat (at ~70 %1RM) maximal power		0.50* 0.70*
Hennesy & Kilty (2001)	17 nationally ranked female sprinters	30 m time			CMJ height (no external load)	n/a	-0.60*
Kukolj et al. (1999)	24 well conditioned PE students	15 m time 30 m time			Average leg power per kg of body mass from continuous jumping protocol according to Bosco (1986)		0.03 0.26
Meckel et al. (1995)	20 female track athletes and 10 recreationally trained females	100 m time	1RM squat (machine)	-0.89**	Maximum power (W / kg) (Wingate 30 s anaerobic test)	N	-0.89**
Mero et al. (1981)	25 sprinters	Maximum running velocity over 30 m			CMJ height (no external load)	n/a	0.65**
Nesser et al. (1996)	20 sportsmen	40 m time			Maximum power (W / kg) Wingate 10 s anaerobic test –	n/a	-0.46*
Piper et al. (2006)	63 division II football players	10 yd time 40 yd time	1RM squat, power clean and jerk	0.48 to 0.81* 0.53 to 0.77*	Leg power estimated by various jumps	n/a	0.48 to 0.81* -0.76 to -0.82*

Study	Sample	Speed test	Strength test	r	Power test		r
Petersen et al. (2006)	19 male and 36 female college athletes	20 yd acceleration 40 yd speed	1RM squat	0.82* 0.85*	CMJ peak power (W)	n/a	0.89* 0.90*
					Standing broad jump		0.73* 0.78*
Sleivert & Taingahue (2004)	30 rugby league, rugby, and basketball players.	5 m time 5 m time			Split squat mean power (W / kg) Split squat peak power (W / kg) Split squat peak force (N / kg) Split squat peak rate of force development N.s^{-1} / kg)	N	-0.68** -0.65** -0.49* -0.54*
					Squat mean power (W / kg) Squat peak power (W / kg) Squat peak force (N / kg) Squat peak rate of force development N.s^{-1} / kg)		-0.64** -0.66** -0.59** -0.40*
Thomas et al. (1996)	19 untrained females	40 yd time			1RM leg press peak power (W)	n/a	0.14
Wisloff et al. (2004)	17 elite soccer players	10 m time 30 m time	1RM half squat	0.94** 0.71**	VJ height (cm)	n/a	0.72** 0.60**
Young et al. (1995)	11 male 9 female track and field athletes (data pooled)	2.5 m time			Peak force (N / kg body mass) Force at 100ms (N / kg body mass) Average power (W / kg body mass) (squat-jump, 19kg external load)	Y	-0.86** -0.73* -0.74*
Young et al. (1996)	18 footballers	20 m time			CMJ (no external load) (cm) CMJ (bodyweight + 50 % bodyweight) (cm)	n/s n/s	-0.66* -0.47

Key: * = Significant at P ≤ 0.05; ** = Significant at P ≤ 0.001; n/a = not applicable; n/s = not stated; RM = repetition maximum; ^ = male unless otherwise specified

Sprint ability over short distances (under 10 m) and longer distances (over 30 m) are considered by many researchers and practitioners to require separate and specific strength qualities (Delecluse et al., 1995; Young, Benton, Duthie, and Pryor, 2001). It has been proposed that concentric strength measures should better relate to starting ability (up to ~10 m) due to this phase having a greater concentric component as compared to later in the sprint where SSC activity is more important (Young et al. 2001). It is also generally considered that shorter sprints require greater contributions of knee extensor activity versus longer sprints that are characterised by greater hip extensor activity (Mero, Komi, and Gregor, 1992). The reported correlations between sprint times over different distances (Baker et al., 1999a; Cronin and Hansen, 2005; Harris, Cronin, and Hopkins, 2008; Nesser et al., 1996; Young et al., 1995) are typically at least very strong ($r = 0.72$ to 0.99), representing a shared variance of 52 to 98%. Hence, some researchers have postulated that the preoccupation with separating strength and power properties associated with different sprint distances may be over-emphasised (Harris et al., 2008), although others claim the shared variance is low enough to justify the different treatments (Cronin and Hansen, 2005; Young et al. 2001). For example, Harris et al. (2008) noted a correlation of 0.87 between 10- and 30-m sprint times, whereas Cronin et al. (2005) reported a correlation of 0.73 between 5- and 30-m sprint times. It would seem most probable and intuitively appealing that there is a variance in sprint ability as distances diverge rather than an arbitrary separation of 'short' and 'long' sprint ability. Hence, practitioners should be mindful of the possibility that the strength and power properties associated with different distances may also progressively diverge. However, given the prevalence of shorter sprints in most sports (Cronin and Hansen, 2005), this review focuses mainly on studies that have investigated distances of up to about 40 m, rather than the 100 m sprint typical of traditional track athletics.

Maximal strength is perceived to be an underpinning neuromuscular quality for athletic performance (Schmidtbleicher, 1985; Stone et al., 2002), but considerable investigation into the relationship between maximal strength and sprinting ability provides the antithesis of such a contention. For example, Baker and Nance (1999a) found trivial to small non-significant relationships between 3RM squat strength and 10 m ($r = -0.06$) or 40 m ($r = -0.19$) sprint times of professional rugby league players. Several other studies (Costill et al., 1968; Cronin and Hansen, 2005; Hasegawa, 2004) have reported very low correlations between maximal strength and sprint measures ($r = -0.01$ to $r = 0.30$). Conjecture remains as other researchers (Wisloff et al., 2004) have reported a near

perfect correlation between squat 1RM and 10 m sprint time ($r = 0.94$), and a very strong correlation between 1RM and 30 m sprint time ($r = 0.71$) in male soccer players. Baker and Nance (1999a) found that squat strength expressed relative to body mass was strongly related to 40 m sprint time of rugby league athletes ($r = -0.66$), and Meckel et al. (1995) reported relative squat strength to correlate highly ($r = -0.89$) with 100 m sprint times. The studies above both utilised squatting movements that incorporated some SSC activity possibly explaining the strong correlations. Baker and Nance (1999a) observed a much lower correlation between squat strength/kg and 10 m sprint time ($r = -0.39$) supportive of such a contention, although SSC activity is not exclusive to top speed sprinting. Moreover, both studies reported strength relative to body-mass, probably more important than absolute strength for activities requiring the movement of one's own body-mass. Harris et al. (2008) and Hasegawa (2004) also noted stronger correlations between strength expressed relative to body-mass and sprint times than absolute strength.

Because sprinting involves efforts of short duration (Mann et al., 1980; Mero, 1988; Tidow, 1990), strength qualities such as the rate of force development or force applied at 100 ms may be more important than maximal strength. Young et al. (1995) investigated the relationship between force measures (concentric only Smith squat-jump with a 19kg bar load from 120° knee angle) and sprinting performance of 20 elite junior track and field athletes (11 males and 9 females). There was no mention whether the pooling of the male and female subjects were investigated for bi-modal distribution (by gender), which can result in artificially high correlations, therefore the magnitude of the correlations need to be interpreted with caution. The best predictors of starting performance (time to 2.5 m) included force relative to body mass generated after 100 ms (F100/mass) from the start of the concentric jump movement ($r = -0.73$) and maximum force ($r = -0.72$). The best predictors of maximum sprinting speed included F100/mass ($r = -0.80$) and maximum force ($r = -0.79$). Using a similar methodology Wilson et al. (1995) found the force at 30 ms in a concentric squat-jump was significantly correlated to sprint performance ($r = -0.62$) and able to effectively discriminate between good and poor performers.

Given the impulse-momentum relationship, impulse is theoretically an important determinant of sprint ability as indicated by biomechanists reporting the determinants of speed via qualitative models (Hay, 1992). This variable therefore should be of greater

interest to the strength and conditioning fraternity, however, impulse has received little attention in the research on predictors of speed. Wilson et al. (1995) investigated the relationship between impulse developed in the first 100ms of a concentric Smith squat-jump (unloaded) from 110° (imp110) and 150° (imp150) knee angles, and sprinting ability over 30 m. Although reported as non-significant, they reported a moderate correlation ($r = -0.49$) between impulse at 150° and sprint ability. Interestingly, the relationship between impulse at 110° and sprint ability was trivial ($r = 0.06$). Perhaps the influence of starting knee angle is critical to the relationship between concentric-only machine squat-jump strength measures and sprint ability. It may be that the length-tension relationship of the hip and knee extensors at lower starting knee angles is biomechanically less specific to the actual knee angles encountered in 10 m sprints. Young et al. (1995) also investigated the relationship between impulse at 100 ms in a squat-jump and sprint times but the correlation was not reported.

Mechanical power output has attracted a great deal of attention in the research and conditioning fraternity in an attempt to clarify its relationship to sprint performance (Baker et al., 1999a, 1999b; Meckel et al., 1995; Sleivert et al., 2004; Thomas et al., 1996; Young et al., 1995; Young et al., 2002) although the aforementioned anomalies with calculation and reporting of power make drawing conclusions problematic. Sleivert and Taingahue (2004) investigated the relationship between 5 m sprint times and power variables in trained athletes from rugby, rugby league and basketball with an average of 2.4 years of RST experience. Average and peak powers were assessed over 30-70 %1RM of concentric only traditional squats and split squats performed in a ballistic manner. Notably, both average and peak power relative to body mass were strongly negatively correlated to 5 m sprint time ($r = -0.64$ to -0.68). The authors chose not to incorporate body mass (system-mass) into the equation for force, asserting that it is not strictly mechanically correct to do so. Sleivert and Taingahue (2004) noted that not using system mass has the effect of markedly reducing power outputs and altering the point on the power-load spectrum where maximal power outputs occur. It is conceivable that excluding system mass may also influence correlational analysis between power variables and sprint times. Similarly, Baker and Nance (1999a) also found strong relationships between relative average power outputs of loaded (40–100 kg) counter-movement Smith-machine jump-squats and sprint times over 10 m ($r = -0.52$ to -0.61) and 40 m ($r = -0.52$ to -0.76). It is not clear from their methodology whether system mass was utilised. In contrast, other studies have reported very low or

non-significant correlations between mechanical power output and speed (Cronin and Hansen, 2005; Harris et al., 2008; Kukolj et al., 1999). Cronin and Hansen (2005) for example, reported small correlations (r = -0.13 to 0.15) between the average power produced during a barbell jump-squat with an external load of 30 kg (calculated with a regression equation from jump height and flight time) and 5 to 30 m sprint times. The authors suggested that the differences between their results and those of Baker and Nance (1999a) were due to the different exercises used for testing (their free-weight versus the fixed vertical plane Smith-Machine), lighter loads used, and differing method of power calculation (their regression versus differentiation from displacement data). Kukolj et al. (1999) attributed their comparatively lower correlations of average leg power per kg body mass with 15 and 30 m sprint times (r = 0.03 and 0.26 respectively) as being partly due to the relative homogeneity of their subject group, or that the unloaded jump-squats used did not elicit maximum power outputs for all subjects.

A number of studies have reported the correlation of simple measures of jump height with sprint performance (Hennessy et al., 2001; Mero et al., 1981; Wisloff et al., 2004; Young et al., 1996). Given that jump height is used to calculate power output, and that power output is assumed to be a determinant of sprint performance, it would be reasonable to assume that higher jump height should be meaningfully correlated to faster sprint times. The research generally supports such a proposition. Hennesy and Kilty (2001), Mero et al. (1981), and Young et al. (1996) all reported strong to very strong correlations between various types of jumps and sprint time / speed over different distances (r = -0.47 to 0.72). Wisloff et al. (2004) though, noted strong positive correlations between vertical jump height and 10 and 30 m sprint times (r = 0.72 and 0.60 respectively). Somewhat ambiguously, the authors reported sprint times (sec) but used the term speed to describe sprint performance. Perhaps correlations were performed between jump height and sprint speed (m/s) but not accurately represented in the reporting of data. It would be otherwise perplexing to explain such an anomaly in results of a simple measure and statistical procedure.

In conclusion, although discrepancies in study design make direct comparisons problematic, there is some indication that strength and power outputs, at least relative to body mass, may be important determinants of sprint performance and therefore worthwhile developing in the pursuit of improved sprint ability. It should be noted though that correlations can only give insights into associations and not into cause and

effect, therefore longitudinal training studies are needed to provide valid information regarding the influence of certain kinematic and kinetic variables/qualities on sprint ability. Such a contention provides the focus of the next section.

Methodological issues affecting training studies

Length of study

The vast majority of research has been short in duration (4-12 weeks) and therefore the application of findings to long-term training is somewhat uncertain as the influence of neural and morphological mechanisms change with training duration (Moritani and deVries, 1979), although significant increases in strength and power have been reported after only four weeks of training (Hammett et al., 2003; Impellizzeri et al., 2008). So-called 'lag-time' (Abernethy et al., 1996; Stone et al., 2002) where strength training effects do not manifest in functional performance until a period of time post-training may also be an issue in short duration studies. Nevertheless, the logistical problems associated with controlling training studies over extended periods make it problematic to adopt such a method. Shorter studies also offer better insight into causal effect than descriptive studies and hence are still worthwhile.

Training volume

Volume is most commonly measured as the total product of repetitions, sets and load (expressed as % 1RM). Equating by volume is the most common method by which research compares the effect of load (contraction force) on various outcome measures. Alternative methods include equating with total time under tension, electromyographic (EMG) activity or total mechanical work performed (Moss, Refsnes, Abildgaard, Nicolaysen, and Jensen, 1997). Cronin and Crewther (2004) suggested that regimes other than volume (sets x reps x load) should be equated to improve identification of the mechanical determinants of strength, power and functional performance. For example, maximal strength is thought best enhanced by training that involves near-maximal tension of essentially non-fatigued muscles (Atha, 1981; Pincivero, Lephart, and Karunakara, 1998). As such, high tension or forces and time under tension are thought to be pre-requisites for optimal strength development. Therefore equating one of these factors would be beneficial to disentangle its effects on strength development. However, the majority of the research in this area has failed to equate loading between

training protocols in any form (Berger, 1962; Harris et al., 2000; Hisaeda, Miyagawa, Kuno, Fukunaga, and Muraoka, 1996; Schmidtbleicher and Buehrle, 1987; Takarada et al., 2000; Wilson, 1993). Therefore, the results from such studies are difficult to interpret, as the reported differences between various training protocols could be a result of differences in training volume rather than specific kinematic and kinetic characteristics of different loading intensities. After an extensive review of strength training research, Atha (1981) concluded that there was little difference between 2RM and 10RM loading in the strengthening effects produced but that a true load-gain relationship was unresolved due to the different number of repetitions required in each loading scheme. Thus, making conclusions about the efficacy of training protocols that are not equated in some manner appears questionable.

An example of this is from the often cited work of Berger (1962) that sought to determine the optimum number of repetitions per set to produce the greatest gains in maximal strength. Six subject groups were defined according to the number of repetitions to failure they performed (either two, four, six, eight, ten, or twelve repetitions). Each group performed only one set so the two-rep group performed a total of only six repetitions per week whereas the 12-repetition group performed 36 repetitions per week. Thus the training groups were not equi-volume. After completing a 12-week training programme the subjects who trained with four, six or eight repetitions produced significantly greater mean changes in 1RM strength compared with those groups that used two, ten or twelve repetitions. Berger (1962) concluded that the optimum number of repetitions per set for improving strength was three to nine. However, the interactions between load and number of repetitions (volume) are impossible to disentangle in such a methodology. That is, both load (contraction force) and volume have some effect on the resulting strength gains but it is impossible to determine their relative contribution from such a design. Furthermore, in practice it is widely accepted that one set, regardless of the number of repetitions or load, is not sufficient volume for optimum strength gains in experienced trainers (Rhea, Alvar, and Burkett, 2002). Therefore extrapolating these findings to common practice is problematic. Despite this, Berger (1962) has frequently been quoted in the literature to justify claims for the optimal training load/force to increase strength. To gain a true appreciation of the effect of contraction force on strength and power development and improved functional performance, research methodologies need to equate the load lifted

in some manner. Research of this kind will improve strength and conditioning knowledge and practice.

Expressing training effects

In the following section the results of each strength and speed measurement have been presented in terms of percent change and effect sizes (ES), and statistical significance where reported. Percent changes in strength and speed are commonly reported in the literature but calculation of percent change does not take into consideration the variance of strength, power and speed improvements (Rhea, 2004). By including the effect size (pre-test minus post-test divided by the standard deviation of the pre-test), the variance of each measurement is included, thus making it a standardised and more accurate description of the treatment effect (Rhea, 2004). The ES allows a comparison of the magnitude of the treatment (training programme) on variables of interest between studies. The effects are described as "trivial", "small", "moderate" and "large" based on the description of effects for untrained, recreationally trained and highly trained athletes (Rhea, 2004). Such classification means that effect sizes are not described in a uniform manner throughout the different populations. For example, an ES of 1.2 is described as "large" for an elite population such as senior rugby-league players (Gabbett, 2006) whereas an ES of 1.3 is described as "moderate" for recreationally active subjects (Kraemer et al., 2000).

Training studies reporting power and sprint performance

Research investigating the effects of different training loads on strength, power and functional performance is abundant, but there are limited number of studies that have allowed for the aforementioned methodological limitations. The following discussion examines studies that have attempted to establish the relative efficacy of different training schemes on isoinertial power measures and sprint ability, and allow for quantification of the relationship between change in power and change in sprint performance. Searches of the literature were performed on the following databases: Medline; SPORT Discus; and Google Scholar years 1960 - 2008. The following keywords were used in different combinations: sprint; speed; strength; training; power; effect(s). A total of 468 subjects were used in the research cited in Table 2.4 of which 19 were females. In terms of age most of the researchers used subjects in their twenties, although some studies used college aged subjects. All subjects were considered at least

'recreationally trained'. The results of the following analysis are most relevant to this demographic.

Changes in jump height and sprint performance

A number of researchers have tracked change in various types of unloaded jump heights and change in sprint times (Coutts et al., 2004; Deane et al., 2005; Gabbett, 2006; Kotzamanidis et al., 2005; Lyttle et al., 1996; Spinks, Murphy, Spinks, and Lockie, 2007; Tricoli et al., 2005; Wilson, Murphy, and Walshe, 1996). The two most common types of jumps assessed are squat jumps initiated from a static start position (typically around 90° knee angle) and the counter-movement jump where the jump is preceded with a rapid dip or descent to a specified position (typically self-selected). It is considered that improving the counter-movement jump should be most associated with improving longer sprints given the use of elastic energy whereas squat jumps may be more useful to short sprints (Young et al. 2001). Ten of the studies reviewed in Table 2.4 assessed change in jump and sprint performance (Coutts et al., 2004; Deane et al., 2005; Gabbett, 2006; Impellizzeri et al., 2008; Kotzamanidis et al., 2005; Lyttle et al., 1996; Spinks et al., 2007; Tricoli et al., 2005; Wilson, Murphy et al., 1996; Wilson et al., 1993). On average, a moderate change (4.7%, ES 0.8) in sprint ability over shorter distances (10 m or less) was associated with a small improvement in squat jump height (5.0%, ES 0.6). For sprints 20 m and over a trivial improvement in sprint ability (1.1%, ES 0.2) was associated with a moderate improvement in squat jump height (7.2%, ES 1.3). Similar relationships were found for countermovement jumps. Thus, it would seem that there is some adaptive association between bi-lateral vertical jump performance and sprint ability, the jump training of greatest influence in short sprints (i.e. 10 m). However, there seems little difference between the jumps in discriminating between the shorter and longer sprint times.

Maximal power training

A number of researchers and practitioners have postulated that training at loads where mechanical power output is maximised (Pmax) is optimal for improvements in functional performance (Baker et al., 1999a; Kaneko, Fuchimoto, Toji, and Suei, 1983; Newton et al., 1994; Sleivert et al., 2004; Stone, 1993; Wilson et al., 1993; Zink, Perry, Robertson, Roach, and Signorile, 2006). Progressing this contention, some studies (Blazevich et al., 2002; Harris et al., 2000) have sought to determine the relative

effectiveness of training with so-called Pmax loads versus other training loads on functional performance. Blazevich and Jenkins (2002) hypothesised that training with loads corresponding to optimum power output (but not actually determined) should result in superior improvements in 20 m sprint times over the course of a 7-week training period in nationally ranked sprinters. One group trained with 30-50 %1RM, and the other 70-90 %1RM. Both groups experienced significant moderate improvements in sprint times (4.3%, ES 0.8) and (2.9%, ES 0.9) for the 70-90 %1RM and 30-50 %1RM groups respectively but there were no significant differences between groups. Power was not measured pre- or post-training, thus it is not possible to quantify whether change in power was related to change in sprint performance.

Harris et al. (2000) examined the effects of training at either high force (80 %1RM), so-called high power (30-45 %1RM - Pmax not actually determined), or a combination of loads using various lower body exercises on strength, power and 30-m sprint time over a 9-week training period. Only the combination training group improved sprint times (1.6%, ES 0.1) described as approaching significance. The high power group experienced a decrement in sprint performance (-0.7%, ES 0.1) albeit insignificantly. Peak power during an unloaded vertical jump improved moderately in both the high power (2.4%, ES 0.9) and combination training (2.6%, ES 0.7) groups, but there were no significant differences between any group. Both Blazevich and Jenkins (2002) and Harris et al. (2000) chose the so-called high power loads based on previous research which reported that power was maximised at approximately 30% of maximum isometric strength (Kaneko et al., 1983; Wilson et al., 1993). Results from these two studies are problematic as total training volume was not equated between groups, so the reported differences between the training protocols could be a result of differences in training volume rather than specific kinematic and kinetic characteristics of the different loading intensities (Harris, Cronin, and Keogh, 2007).

McBride et al. (2002) investigated the effect of equi-volume training using either heavy (80 %1RM) or light (30 %1RM) load jump-squats on the development of sprint ability, strength and power outputs. The 30 %1RM load was used based on the assumption that it was close to the maximal power load for the jump-squat, but individual Pmax was not determined. Subjects were athletic, well-trained males; training was conducted over eight weeks and was equated by number of sets. Notably, both groups were instructed to perform training as explosively as possible, irrespective of actual movement velocity.

The 30 %1RM group experienced trivial (non-significant) improvements in all sprint times, whereas the 80 %1RM group's sprint times were significantly slower post-training, although only change in 10 m sprint time was significantly different between groups. Significantly greater changes in jump-squat peak power at 30 %1RM occurred in the 30 %1RM group (10.0%, ES 0.4) than the 80 %1RM group (3.0%, ES 0.1). The 30 %1RM group also experienced trivial but significant increases in jump-squat peak velocity at all loads tested (8.1, 7.3, and 8.6% at 30, 55 and 80 %1RM respectively, ES ~ 0.1) compared to the non-significant changes of the 80 %1RM group (-0.5, 2.1, and 3.7% respectively, ES 0.0) although only the change in peak velocity at 30 %1RM was considered significantly different between groups. McBride et al. (2002) commented that the results supported the use of lighter loads performed in a ballistic manner in training for functional performance despite superior improvement in only one of the functional performance measures.

A common assumption of many authors is that power is maximised at loads of 30 to 45 %1RM, (Baker, 2001a; Bemben, Rohrs, Bemben, and Ware, 1991; Kaneko et al., 1983; Mayhew, Johns, Ware, Bemben, and Bemben, 1992; Wilson et al., 1993). However, there are large inter-individual, and exercise specific differences in the load where Pmax occurs (Harris, Cronin, and Hopkins, 2007a; Sleivert et al., 2004). Hence, it would seem important to specifically identify the load where Pmax occurs for each individual subject on specific exercises to adequately investigate the effects of Pmax training on force, power and functional performance. Neither Blazevich et al. (2002), Harris et al. (2000) nor McBride et al. (2002) identified the load associated with Pmax for each individual, or for the respective resistance training exercise used for both testing and training. Only three studies to date have attempted this (Cormie, McCaulley, and McBride, 2007; Newton, Rogers, Volek, Hakkinen, and Kraemer, 2006; Wilson et al., 1993), but each is characterised by its own methodological limitations that make interpretations and comparisons difficult.

Cormie et al. (2007) compared the effects of twelve weeks of jump-squat training at individual Pmax load versus combined heavy (90 %1RM) and Pmax load training on jump-height and peak power output during counter-movement jump-squats at various loads in recreationally trained males. The method of determining and calculating Pmax was clearly defined and training was equated by total work done but results were presented graphically thus precise calculation of percent change and ES was not

possible. Both groups significantly improved peak power output per kg body-mass and jump-height at the lighter testing loads (data not reported), but sprint times were not assessed.

Newton et al. (2006) reported that four weeks of Smith-machine jump-squat training at the load where mechanical power was maximised for each individual significantly improved jump performance (5.4%, ES 0.6) in women volleyball athletes during a competitive season. Peak power during a loaded (Pmax load) Smith-machine jump-squat also improved post-training (4.9%, ES 0.4, not significant), and average power improved moderately and significantly (8.5%, ES 0.6). Sprint performance was not reported. No control group or alternative training groups were investigated owing to the ethical issue of using elite competitive athletes in-season as subjects, so no comparison could be made to other training modalities, thus limiting the validity of determining the superiority of such training. Additionally, although it was specifically noted that training loads were continually adjusted to the point where maximal mechanical power was maximised for each individual, the methods used for determining peak power were not clear and the loads used during training were not reported as %1RM thus applying the recommendations to a practical setting is problematic.

Wilson et al. (1993) also investigated the effect of training with individual Pmax loads over a 10-week period. One group trained with maximal power loads but, in contrast to the study by Newton et al. (2006), Pmax was identified as the load which maximised mean mechanical power output rather than peak mechanical power output. It was stated that loads were around 30% of maximum isometric force. Two other groups trained with either heavy loads (6-10 RM or ~75 − 84 %1RM), or with body-weight jumps. Pre- and post-testing included 30-m sprint times and jump height. The Pmax training resulted in a trivial decrease in sprint times (-1.5%, ES 0.2) described as approaching statistically significant whereas sprint times for the other two training groups were virtually un-changed (-0.2%). The Pmax group also experienced significantly greater gains in jump height (14.8%, ES 1.0) than the other groups (6.3%, ES 0.3 and 6.5%, ES 0.3 for the heavy load and body weight groups respectively) pre- to post-training. The authors concluded that their results strongly suggest the superiority of training at Pmax loads for the improvement of athletic performance and stated that loads of 30% of maximum should be used. However, the study suffers from a similar methodological problem to that of Newton et al. (2006) in that the methods for determining Pmax were

not clearly described, and volume was not equated between training groups. Additionally, isoinertial power output was not assessed, so establishing any relationship between change in power output and change in functional performance is not possible.

No study to date has specifically identified peak power outputs for each individual on the specific isoinertial resistance training exercise used in both testing and training, tracked strength and power outputs on that exercise and related these changes to change in sprint ability over a training period.

Change in power and sprint performance

Cronin et al. (2007) reviewed training studies that assessed strength effects on sprint times and concluded that, for highly trained athletes moderate to large (ES = 0.71 to 1.2) 1RM squat strength changes (~12%) may be needed for moderate (ES = 0.74 to 0.94) changes (> -2.0%) in sprint time. Of interest then, is the relationship between change in power output and change in sprint ability. Of the studies reviewed in Table 2.4, six assessed both peak power and sprint ability pre- and post- training (Hammett et al., 2003; Harris et al., 2000; Hoffman et al., 2005; Kraemer et al., 2000; McBride et al., 2002; Murphy et al., 1997). Of the total 153 subjects all except six were male, and all were at least recreationally trained athletes competing at a range of levels. On average, a trivial increase (6.6%, ES 0.3) in peak power output was associated with a trivial improvement (1.3%, ES 0.2) in sprint performance for distances greater than 20 m. Only one study (McBride et al., 2002) examined and reported change in lower-body isoinertial peak power and change in sprint ability over shorter distances. A small decrement (2.2%, ES 0.4) in sprint ability (average of 5- and 10-m times) was associated with a small improvement (10.3%, ES 0.4) in jump-squat peak power (average of both training groups). Furthermore, of the twelve studies in Table 2.4 that compared the effects of different training programmes on sprint performance, only six (Harris et al., 2000; Hoffman et al., 2004; Hoffman et al., 2005; Kotzamanidis et al., 2005; McBride et al., 2002; Wilson et al., 1993) reported significantly greater sprint improvements in one group versus another. Of those six, only one (Kotzamanidis et al., 2005) noted within group concurrent significant improvements in both sprint and power measures. Thus, it remains uncertain as to whether or not improving power output in gym-based exercises such as the squat and its derivatives is practically beneficial to improving sprint ability, particularly in highly trained individuals.

Table 2.4. Training studies tracking change in isoinertial power measures and change in sprint ability

Study	Subjects^ (excluding non-training controls)	Sprint performance measure	Power measure System mass used? Y/N	Training groups Duration, equi-volume? Y/N	Percent change in sprint performance with effect size Δ% (ES)	Percent change in power measure with effect size Δ% (ES)
Coutts et al. (2004)	42 development rugby league players	10 m time 20 m time	Countermovement vertical jump (CMJ) height (cm) System mass n/a	Supervised or unsupervised back squat 4-10RM and unloaded box-jumps 12 weeks, equi-volume Y	10 m time 0.9% (0.3)* 40 m time 0.9% (0.4)*	9.0% (0.7)* (Supervised group)
Deane et al. (2005)	24 physically active but not currently weight-training college students (11 M, 13 F)	10 yd time 40 yd time	Unloaded CMJ height (cm) System mass n/a	Standing hip flexion against elastic resistance at ~10RM 8 weeks, equi-volume n/a	10 yd time 10.7% (1.4)* 40 yd time 3.8% (0.6)* (ave M and F)	-1.5% (0.2) (ave M and F)
Gabbett (2006)	77 junior elite rugby-league players	10 m time 20 m time 40 m time	Unloaded vertical jump (VJ) height (cm) System mass n/a	All subjects: Pre-season field conditioning programme including sprint drills 14 weeks, equi-volume n/a	10 m time -1.1% (0.1) 20 m time 0.6% (0.0) 40 m time -0.2% (0.1) (ave for all subjects)	6.2% (1.5)*

Harris et al. (2000)	51 football athletes	30 m time	Unloaded VJ peak power (W)	High force group (HF) 80 %1RM squats & derivatives	HF group 0.0% (0.0)	HF group 2.6% (0.1)	
			System mass n/a	High power group (HP) 30-45 %1RM squats & derivatives	HP group -0.7% (0.1)	HP group 2.4% (0.1)*	
					COM group 1.4% (0.1)*#	COM group 2.6% (0.1)*	
				Combination group (COM) 30-80 %1RM			
				9 weeks, equi-volume N			
Hammett & Hey (2003)	19 high school student athletes (13 M, 6 F)	40 yd time	Unloaded VJ peak power (W)	Experimental group (EXP) Full-body weights, plyometrics and sprint drills. Ballistic single hip & knee extension for 10 s over-speed and sprint drills	EXP group 2.7% (0.4)*	EXP group 1.0% (0.0)*	
			System mass n/a		CON group 1.2% (0.2)*	CON group 2.3% (0.1)*	
				Control group (CON) Full-body weights, plyometrics and sprint drills.			
				4 weeks, equi-volume n/a			
Hoffman et al. (2004)	20 division III football players	40 yd time	Unloaded CMJ power (W)	Olympic lift group (OL) Various Olympic derivative weightlifting exercises	OL group 1.4% (0.4)#	OL group 8.2% (0.9)	
			System mass n/a		PL group 0.8% (0.3)	PL group 16.3% (0.8)	
				Power lift group (PL) 4-8RM weight training			
				Both groups also sprint drills			
				15 weeks, equi-volume N			

Hoffman et al. (2005)	31 college football players	40 yd time	Jump-squat machine (70 %1RM) peak power (W / kg) System mass n/s	Concentric only group (C) 70 %1RM concentric only Concentric / eccentric group (CE) 70 %1RM eccentric and concentric load 5 weeks, equi-volume N	C group 1.8% (0.3)# CE group 0.4% (0.0)	No significant differences in change in power outputs (data not reported)
Impellizzeri et al. (2008)	44 amateur soccer players	10 m time	Unloaded VJ height (cm) Unloaded CMJ height (cm)	SAND group Various unloaded plyometric exercises on sand GRASS group Various unloaded plyometric exercises on sand 4 weeks, equi-voulme Y	SAND group 4.3% (0.9) GRASS group 3.7% (0.9)	VJ SAND group 10.2% (0.8)* GRASS group 5.3% (0.6) CMJ SAND group 6.5% (0.7)* GRASS group 14.6% (1.5)*#
Kotzamanidis et al. (2005)	23 soccer players	30 m time	Unloaded VJ height (cm) Unloaded CMJ height (cm)	Strength group (STR) Weight training 3-8RM Combination group (COM) Weight training 3-8RM and sprint drills 9 weeks, equi-volume N	STR group 0.5% (0.1) COM group 3.5% (0.9)*#	VJ STR group 1.9% (0.2) COM group 7.8% (0.8)*# CMJ STR group 1.1% (0.1) COM group 6.8% (0.7)#

Study	Subjects	Performance tests	Training measures	Intervention	Sprint results	Power/jump results
Kraemer et al. (2000)	17 moderately trained men	40 yd time 60 yd time	Unloaded CMJ peak power (W) Jump-squats (30 %1RM) peak power (W) System mass n/s	Meridian shoe group (MS) Full-body weight training and meridian shoes worn during sprint and plyometric training Athletic shoe group (AS) Full-body weight training and normal athletic shoes worn during sprint and plyometric training (Identical except for shoes) 8 weeks, equi-volume Y	40 yd sprint time MS group 1.7%* AS group 2.3%* 60 yd sprint time MS group 3.4%* AS group 2.2%* (best times) Effect sizes not avail.	VJ peak power MS group 4.3% (0.3) AS group 3.5% (0.3) Jump-squat power MS group 2.6% (0.1) AS group 2.1% (0.1)
Lyttle et al. (1996)	22 regional level athletes	'Flying' 20 m time 40 m time	Unloaded CMJ height (cm) Unloaded VJ height (cm) System mass n/a	Maximum power group (MP) Squat-jumps at individually determined peak power output ~30%1RM Combination group (COM) Squats 6-10RM and rebound depth jumps no external load 8 weeks, equi-volume N	20 m time MP group 1.2% (0.2) COM group -0.4% (0.1) 40 m time MP group -1.3% (0.2) COM group 0.7% (0.2)	CMJ MP group 7.5% (0.4)* COM group 10.6% (0.5)* VJ MP group 18.3% (0.9)* COM group 16.6% (0.7)*
McBride et al. (2002)	19 club level athletes	5 m time 10 m time 20 m time	Jump-squat machine at 30, 55, and 80 %1RM peak power (W) System mass n/s	30 %1RM group (JS30) Jump-squats 30 %1RM 80 %1RM group (JS80) Jump-squats 80 %1RM 8 weeks, equi-volume Y	5 m time JS30 group 0.9% (0.1) JS80 group -6.4% (0.5)* 10 m time JS30 group 1.6% (0.2)#	30 %1RM JS30 group 10.0% (0.4)* JS80 group 3.0% (0.1)* 55 %1RM JS30 group 13.0% (0.5)*

Study	Participants	Speed measure	Power measure	Training groups / protocol	Results	Results
					JS80 group -4.9% (0.7)	JS80 group 9.3% (0.5)*
					20 m sprint JS30 group 0.9% (0.1) JS80 group -1.6% (0.2)	80 %1RM JS30 group 16.4% (0.6)* JS80 group 10.2% (0.4)*
Murphy & Wilson (1997)	27 recreational athletes	40 m time	10kg loaded squat-jump rate of force development (RFD) (N.s⁻¹) 6 sec cycle (CYC) peak power (W)	Squat 6-10RM 8 weeks, equivolume n/a	2.2% (0.4)*	RFD 13.2% (0.4) CYC 8.9% (0.5)
Spinks et al. (2007)	20 first grade rugby and football athletes	0-15 m velocity (m/s)	Unloaded CMJ height (cm)	Resisted sprint group (RS) Resisted and non-resisted sprint training Non-resisted sprint group (NRS) Non-resisted sprint training 8 weeks, equi-volume N	RS group 7.8% (1.6)* NRS group 6.2% (1.0)*	RS group 5.9% (0.5)* NRS group 9.1% (0.9)*
Tricoli et al. (2005)	15 college students with previous weight training experience	10 m speed (m/s) 30 m speed (m/s)	Unloaded VJ height (cm) System mass n/a	Weightlifting group (WL) Half squat 6RM and various Olympic derivative weightlifting movements Vertical jump group (VJ) Half squat 6RM and various jumping drills 8 weeks, equi-volume N	10m sprint time WL group 3.7% (0.9)* VJ group 2.7% (0.5) 30 m sprint time WL group 0.1% (0.0) VJ group 0.8% (0.1)	WL group 9.5% (1.5)* VJ group 2.7% (0.2)

Wilson et al. (1993)	64 recreational athletes	30 m time	4kg loaded CMJ height (cm) 4kg loaded VJ height (cm)	Weight training group (WTS) Squat 6-10RM Plyometric training group (PLYO) Unloaded depth jumps Maximum power group (Pmax) Loaded machine jump-squats at individually determined maximum mean power output (~30% of maximum isometric force) 10 weeks, equi-volume N	WTS group 0.2% (0.0) PLYO group 0.2% (0.0) Pmax group 1.1% (0.2)	CMJ WTS group 4.8% (0.3)* PLYO group 10.3% (0.6)* Pmax group 16.8% (1.0)*# VJ WTS group 6.3% (0.3)* PLYO group 6.5% (0.3) Pmax group 14.8% (1.0)*#
Wilson et al. (1996)	14 previously weight training exercise science students	40 m time	Unloaded CMJ height (cm)	Squat 6-10RM 3 weeks, equi-volume n/a	2.2% (0.4)*	21.2% (1.3)*

* = Significant pre- to post-test at P ≤ 0.05; # = significant pre- to post-test between group difference; n/a = not applicable; n/s = not stated; ^ all subjects male unless otherwise stated.

Conclusions

Gym-based training is based on the fundamental premise that the mechanisms underlying strength and power improvements will transfer (to some degree) to functional performance enhancement. Quantification of such a premise has proved problematic though. Although research has evolved, methodological differences and ambiguities mean that research to-date still provides limited insight into the strength and power qualities that are worthwhile developing in the pursuit of improved functional performance. In particular, there has been a great deal of interest in the strength and power outputs of the squat and their relationship to performance measures such as sprint ability. Maximal strength and mechanical power output have attracted considerable research attention but their importance to enhancing sprint performance remains unclear. Further investigation that addresses the aforementioned methodological discrepancies is needed to clarify and quantify strength and power outputs of prognostic and diagnostic value. It may be that instrumentation of squats and derivatives with the intention of extracting power measures meaningfully related to sprint performance is patently limited by a fundamental lack of biomechanical specificity to sprinting.

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CHAPTER 3. POWER OUTPUTS OF A MACHINE SQUAT-JUMP ACROSS A SPECTRUM OF LOADS

Prelude

The load that maximises mechanical power output (Pmax) in gym-based resistance training exercises has received considerable research attention owing to its perceived importance to training prescription. Of particular interest to researchers and practitioners alike are the outputs associated with the commonly prescribed squat-jump exercise. Currently though, there is limited and contradictory research on the power outputs associated with squat-jumps across a full spectrum of loads in well-trained athletes. Reported loads at which Pmax occurs in squat-jumps range from 0 – 63 %1RM and it appears that Pmax is exercise and individual specific. Furthermore, the research seeking to quantify the difference in power outputs of loads either side of peak power output load is very limited. It may be that identifying Pmax is of less importance if the difference in power output about Pmax is insubstantial. The purpose of this study therefore was to address previously identified discrepancies in research methods to quantify the concentric force-velocity-power outputs of a machine squat-jump across a spectrum of loads (10-100 %1RM). Since power is the product of force and velocity, it was thought that analysis of these variables would allow for a more detailed understanding of the movement capability of muscle thus providing specific diagnostic information for subsequent investigations into the relationships between Pmax and functional performance measures.

Introduction

Power can be defined as the rate at which mechanical work is performed or as the product of force and velocity, and is commonly perceived to be critical to the performance of many athletic tasks (Abernethy et al., 1995; Harman, 1993; Sale, 1991b). Consequently the development of power has been the subject of much research and subsequent conjecture, particularly the improvement of power through the use of resistance strength training (RST). Of interest to strength and conditioning practitioners is identifying the load that maximises peak and/or mean power output (Cronin and Sleivert, 2005; Harris et al., 2000; McBride et al., 2002; Wilson et al., 1993). In terms of the point on the power-load spectrum where Pmax occurs (Pmax load), some research (Baker, 2001a; Sleivert et al., 2004) has suggested that power output at loads each side of Pmax load are not substantially different to the Pmax. As a result the emphasis on identifying the load that maximises power output may be overstated. However, no research to date has quantified the magnitude of these differences around Pmax.

In terms of lower body exercises, squats and squat-jumps appear to be the exercises most widely researched and used in practice (Baker, 2001a; Baker et al., 2001; Dugan et al., 2004; Duthie, Young, and Aitken, 2002; McBride et al., 2002), but the reported strength and power outputs vary greatly. Many of the discrepancies found in the strength literature can be attributed to methodological factors. First, the different types of dynamometry (isometric, isokinetic, isotonic and isoinertial) used to assess strength and power. It is generally recognised that isokinetic and isometric assessment bear little resemblance to the accelerative/decelerative motion implicit in limb movement during resistance training and sporting performance. Additionally, some investigators have investigated only a sample of the load spectrum (e.g. 30, 60 and 90 %1RM) and made inferences from such an approach (Kaneko et al., 1983; McBride et al., 2002; Weiss et al., 2002). Investigation of a full spectrum of loads provides a greater insight into the kinematic and kinetic characteristics of respective exercises and enables a more precise calculation of Pmax and subsequent differences around this point.

The technique used also influences the kinematics and kinetics of the movement. During traditional weight training the bar and/or load reaches a velocity of zero at the

end of the concentric phase, therefore deceleration has been found to occur for a considerable portion of the contraction (Cronin, McNair, and Marshall, 2001a; Elliott et al., 1989; Wilson et al., 1993). For example, loads of 81 %1RM resulted in deceleration for 51.7% of the concentric phase during a bench press where the grip was maintained on the bar at the end of the concentric phase (Elliott et al., 1989). An alternative technique where the load (bar and/or oneself) is projected as in jumping and throwing has been termed 'ballistic' training. These techniques increase the overall duration of the acceleration phase and therefore increase force and power production when compared to traditional explosive techniques (Newton and Wilson, 1993; Newton, Kraemer, Hakkinen, Humphries, and Murphy, 1996). Additionally, the joint angles, range of motion, contraction type, and instructions issued to subjects may all influence the final outputs (Dugan et al., 2004). For example, it is important to distinguish between movements that involve stretch shortening cycle activity and those which are concentric only as there are clear differences in the respective kinematics and kinetics (Cronin, McNair, and Marshall, 2000).

The variety of methods used to calculate the power output also makes comparison between studies difficult. It is thought appropriate to use system mass (inclusion of body mass) to calculate loading intensity during ballistic lower body exercises because the subject must propel themselves and the mass associated with the bar. Excluding body mass from the calculation decreases the total mass component of force therefore decreasing total power output and affects the load at which Pmax occurs, although there is some conjecture regarding this (Dugan et al., 2004; Sleivert et al., 2004). Disentangling meaning from the research on power outputs is also challenging due to the diversity of strength and power measures used and misrepresentation of findings. For example, some studies do not differentiate between peak power and mean power, or it is unclear which of these two variables have been reported (Baker et al., 1999b; Garhammer, 1980).

Finally, there is some evidence suggesting that subjects with greater strength training and/or athletic experience produce different power outputs than their less experienced counterparts (Baker, 2001a; Stone, O'Bryant et al., 2003). Indeed, if improvement of athletic performance were of primary interest to the researcher, the use of athletic subjects with a resistance training background would appear to provide greater practical

value. Cognizant of these methodological limitations, the purpose of this study was to describe the kinetics and kinematics associated with machine squat-jumps across loads of 10 – 100 %1RM in well-trained athletes and in particular identify the load that maximises power output (mean and peak) and quantify the power output of loads either side of Pmax.

Methods

Approach to the problem

To determine power outputs and the associated point on the load spectrum where power was maximised, subjects performed machine squat-jumps across loads of 10-100 %1RM. Thereafter, a quadratic was fitted to each subject's power-load curve, and decreases in power output at 10 and 20% either side of Pmax determined.

Subjects

Eighteen male subjects volunteered to participate in this study. The mean age, mass, and height of the subjects were 23.1 ± 2.7 years, 105.6 ± 13.4 kg, and 183.1 ± 4.4 cm respectively. All subjects were from a National level rugby training squad with an extensive resistance training background (5.2 ± 2.4 yrs), and had recently completed a two-month period of pre-season resistance training including squat-jumps utilizing a range of resistances, and some plyometric training drills. Each subject had the risks of the investigation explained to them and signed an informed consent prior to participation. The Human Subject Ethics Committee of the Auckland University of Technology approved all procedures undertaken in this study.

Equipment

Subjects performed their assessments on a customised standing hack-squat machine (Fitness Works, Auckland, NZ). The hack-squat machine used a plate-loaded sled allowing vertical movement on low friction sliders (see Figure 3.1). It was similar to a standard Smith machine, but included padded shoulder supports to allow subjects to perform safe maximal squats or explosive squat-jumps. The starting position of the sled was adjustable to the nearest 3mm, allowing lower limb joint angles to be standardised

as measured by a goniometer. A linear position transducer (P-80A, Unimeasure, Oregon – mean sensitivity 0.499 mV/V/mm, linearity 0.05% full scale) was attached to the sled and measured vertical displacement of the bar with an accuracy of 1.0mm. Data was sampled at 1000 Hz and collected via a computer based data acquisition and analysis program (Labview[TM] 6.1. National Instruments, Austin, Texas).

Figure 3.1. Customised hack-squat machine

Procedures

The maximal strength (1RM) and concentric power-load spectrum (10-100 %1RM) was assessed for each subject on two separate sessions spaced no more than four days apart. Instructions were issued to subjects to standardise pre-test preparation (exercise levels, nutrition, etc.) as much as possible in the 24-hour period preceding the testing session. At each session the subjects first performed a standardised warm-up procedure consisting of five minutes running on a treadmill (Powerjog GX2000, Birmingham, UK) at a speed of nine kilometres per hour and an incline of two percent. During the first session, subjects first performed two warm-up sets at a light load (40-60 kg). Two to three trials were then performed to establish 1RM. Adjustable mechanical brakes were used to fix the stop-start position at 110° knee angle (using a goniometer centred at the lateral epicondyle of the knee and aligned to the lateral malleolus and greater trochanter). Foot position was self selected by subjects but standardised to within five centimetres between all subjects. A load of 10% of the individual's 1RM was then placed on the squat machine and the subjects completed one lift with maximal effort. A

one-minute rest period was then allowed before the lift was repeated. The load was then increased to 20% of the individual's 1RM, and the process repeated. Loads assessed were 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% of the individual's 1RM. In order to negate any order or fatigue effect starting load was randomised. Subjects were given instructions to move every load with maximal effort and jump if the load permitted. All lifts were commenced from the standardised starting position thus concentric force was measured with no eccentric counter-movement. This procedure was repeated on another testing occasion no longer than four days later.

Data analysis

The displacement time data were filtered using a low (second order) pass Butterworth filter with a cut-off frequency of 5 Hz. This filtered displacement time data was then differentiated to determine velocity (displacement / time) and acceleration (velocity / time). Force values were calculated as the sum of the product of the mass (load and body mass) by gravity and the product of mass and acceleration (see equation 1).

Equation 1: $F = mg + ma$

From this data the following concentric variables were calculated from the mass-displacement characteristics of the mass lifted (including body mass) from the start of the upward movement to the peak concentric displacement: mean and peak velocity; mean and peak force; mean and peak power.

The measurement of force as described in this experiment has been verified by comparison of the linear transducer data with data gathered simultaneously from an accelerometer and a force platform across movement types (concentric only and rebound bench presses - squat, countermovement and drop jumps), loads (40 - 80 %1RM) and sampling frequencies (200-1000 Hz). The data from the linear transducer was shown to be reliable (ICC = 0.92-0.98 for measures of mean and peak force) and valid across these conditions. The reliability of the procedures has been reported previously (Cronin et al., 2000).
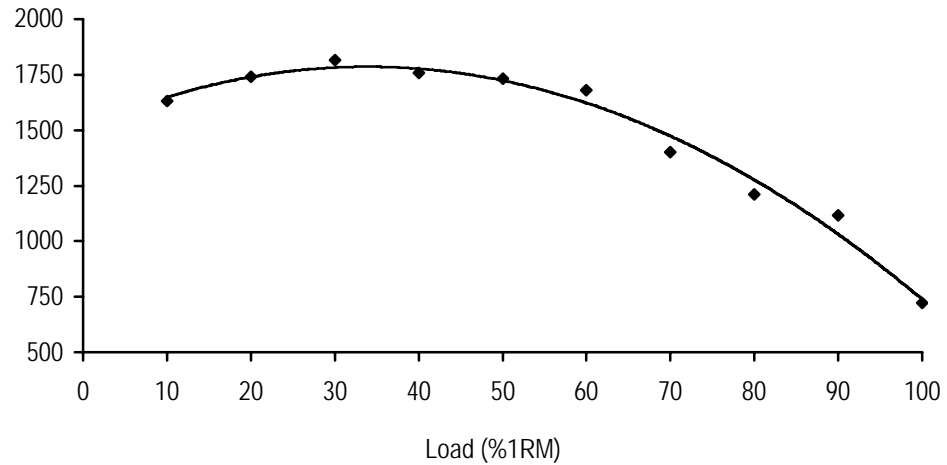
Statistics

Means and standard deviations were used throughout as measures of centrality and spread of data. To estimate the load that maximised mechanical power output a quadratic was fitted to each subject's power output (in Watts) and load (in %1RM). The goodness-of-fit of the quadratic was expressed as an overall correlation coefficient (R) calculated by taking the square root of the fraction of the variance explained by the model, after adjusting for degrees of freedom. The curve was also used to estimate the percent decline in power output at loads of 10 and 20 %1RM either side of the maximum power output. These declines were presented as means and standard deviations, and their magnitudes and confidence limits were interpreted qualitatively (Batterham and Hopkins, 2006). Confidence limits for means were derived by appropriate application of the t-statistic in a spreadsheet. Confidence limits for the standard deviation were derived by application of the chi-squared statistic in a spreadsheet (downloaded from newstats.org/xcl.xls). Measures of reliability were also derived from a spreadsheet (newstats.org/xrely.xls); within-trial reliability is presented as coefficients of variations (CV), and between trial reliability is presented as CV and intra-class correlation coefficients (ICC).

Results

The mean squat 1RM was 280 ± 50 kg and the mean relative 1RM (1RM/body mass) was 2.67 ± 0.46 kg per kg body mass. Force and velocity data were found to be typical of those expected from a spectrum of loads ranging from 10 – 100 %1RM. The group means for peak force ranged from 2490 ± 350 N at 10 %1RM to 4590 ± 820 N at 100 %1RM. Mean force ranged from 1230 ± 150 N at 10 %1RM to 3740 ± 570 N at 100 %1RM. The group means for peak velocity ranged from 1.90 ± 0.15 m.s^{-1} at 10 %1RM to 0.48 ± 0.14 m.s^{-1} at 100 %1RM. Mean velocity ranged from 1.07 ± 0.10 m.s^{-1} at 10 %1RM to 0.24 ± 0.08 m.s^{-1} at 100 %1RM.

Figure 3.2. Representative mean power-load curve for the machine squat-jump of one subject
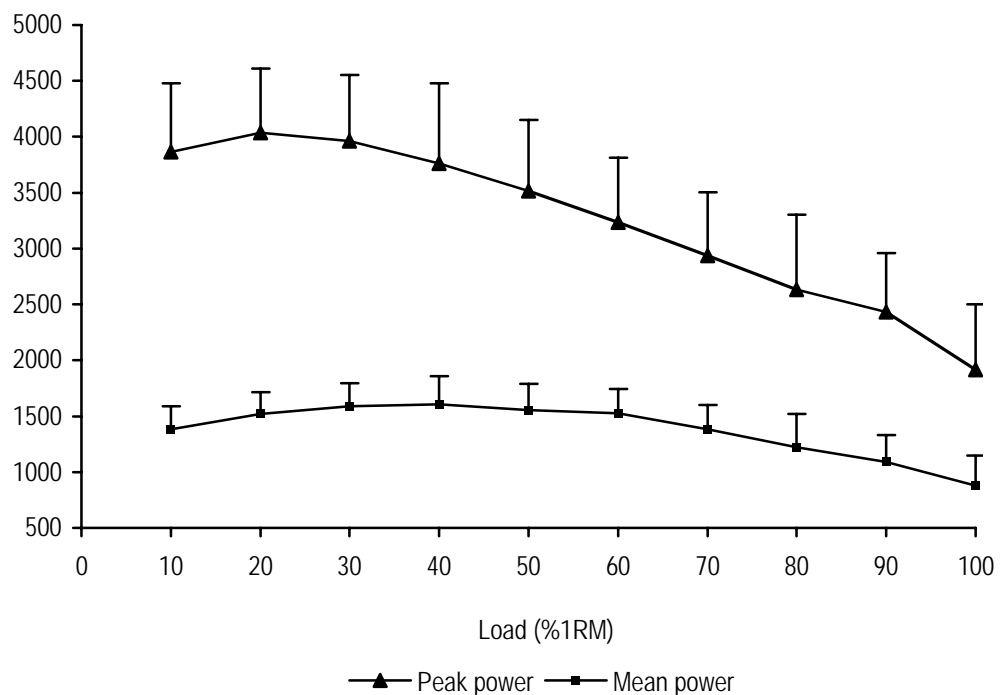

A typical power-load graph for a representative subject is shown in Figure 3.2. With respect to peak power for all subjects (see Figure 3.3), an estimated load of 21.6 ± 7.1 %1RM (mean $\pm$ SD) was found to maximise peak power output (mean goodness of fit R $= 0.94$). A 10 and 20% change in load each side of this maximum resulted in a decrease in Pmax of 3.0 and 9.9% (90% confidence limits $\pm 2.4\%$) respectively. Individual differences about these means were standard deviations of 2.6 and 6.0% respectively (90% confidence limits $\times \div 1.34$). The group peak power output was 4110 ± 570 W, and relative peak power output was 38.4 ± 4.1 W per kg body mass. The individual mean Pmax ranged from 10 to 35 %1RM. When rank ordered into strongest and weakest according to 1RM, the strongest were found to have a mean Pmax load of 18.1 %1RM whereas the weakest groups mean Pmax load was 25.3 %1RM.

In terms of mean power (see Figure 3.3), an estimated average load of 39.0 ± 8.6 %1RM was found to maximise power output (mean goodness of fit R $= 0.91$). A 10 and 20% change in load each side of this maximum resulted in a decrease of 1.4 and 5.4 % (90% confidence limits $\pm 2.4\%$) respectively. Individual differences about these means were standard deviations of 0.2 and 2.1% respectively (90% confidence limits $\times \div 1.34$). The group absolute mean power output was 1620 ± 200 W, and relative mean power output 15.4 ± 2.0 W per kg body mass. The individual mean Pmax ranged from 22 to 57 %1RM.

In terms of the point on the power-load spectrum where Pmax occurred, reliability between trials was 6.2%; 0.92 (CV;ICC), and 5.7%; 0.86 for peak and mean power respectively. In terms of Pmax output reliability was 6.0%; 0.61, and 7.4%; 0.45 for peak and mean power respectively.

Figure 3.3. Power outputs across loads of 10-100 %1RM. Data are means; bars are standard deviations.

Discussion

Maximal strength as measured by a 1RM squat, were considerably higher in the present study than reported in other similar research (Baker, 2001a; Izquierdo et al., 2002; Sleivert et al., 2004; Stone, O'Bryant et al., 2003; Weiss et al., 2002). Mean squat 1RM was 280 ± 50 kg and the mean relative 1RM (1RM/body mass) was 2.67 ± 0.46 kg per kg body mass. This could be attributed to the higher starting position ($110°$ knee angle) of the squat used in this study, enabling a more forceful movement due to an advantageous length-tension relationship in the knee and hip extensors. Similarly, Sleivert and Taingahue (2004) explained the significant differences in the force-

61

velocity-power profile between the split squat (206.6 ± 34.4 kg) and traditional jump squats (149.5 ± 22.6 kg) reported in their study as being due to the difference in starting position between the exercises. That is, due to the lower start position of the traditional squat (90° knee angle), the load was difficult to move initially, but comparable velocities to the split squat were achieved later in the lift.

The power outputs observed in the present study are comparable to the limited number of other studies using similar methodologies (Baker, 2001a; Baker et al., 2001; Bourque and Sleivert, 2003; McBride, Triplett-McBride, Davie, and Newton, 1999; Stone, O'Bryant et al., 2003), that is, where resistance trained subjects have performed a ballistic squat movement and body mass has been included in the equation for power. Where one or a combination of these factors is omitted from the research design, lower power outputs are mostly reported (Dugan et al., 2004; Esliger and Sleivert, 2003; Izquierdo et al., 1999; Thomas et al., 1996; Weiss et al., 2002). For example, Thomas et al. (1996) reported an average group mean power output of 404 ± 22 W which could be attributed to the subject's untrained status, female gender, or the different movement used (double leg press). The study design of Esliger and Sleivert (2003) was very similar to the current study in that it examined maximal effort jump squats in resistance trained athletes across a spectrum of loads. The only notable differences in methodology were the exclusion of body mass in the equation for power and a lower starting angle at the knee (90°). Peak power output was reported as 1766 ± 479 W. Additionally, the type of instructions issued to subjects may influence power outputs (Dugan et al., 2004).

A common assumption of many authors is that power is maximised at a load of 30 to 45 %1RM, and often only the mean response (%1RM = Pmax) for the population being studied is reported (Baker, 2001a; Bemben et al., 1991; Kaneko et al., 1983; Mayhew et al., 1992; Moss et al., 1997; Newton et al., 1997; Wilson et al., 1993). More recently, investigators have adopted a "bandwidth" approach to reporting Pmax load, suggesting that there is a range of loads that maximise power output or more likely that there are large inter-individual differences in Pmax (Baker, 2001a; Sleivert et al., 2004). The reported range of loads in the literature that maximise peak power outputs for lower body exercises vary from 0 – 70%1RM for peak power, and 30 – 70%1RM for mean power (Baker et al., 2001; Izquierdo et al., 2002; Kawamori and Haff, 2004; Sleivert et

al., 2004; Stone, O'Bryant et al., 2003; Weiss et al., 2002). The Pmax loads observed in the present study (21.6 ± 7.1 %1RM and 39.0 ± 8.6 %1RM peak and mean power respectively) were lower than reported in much of the literature (Esliger et al., 2003; Siegel, Gilders, Staron, and Hagerman, 2002; Sleivert et al., 2004; Thomas et al., 1996; Weiss et al., 2002), and may, in part, be due to the inclusion of body mass in the equation for power in the current study. Excluding body mass will cause a substantial shift toward the heavier end of the load spectrum where Pmax occurs and cause a proportionately larger error in calculation of power at lighter loads (Dugan et al., 2004). The range for Pmax loads across all subjects (10 to 35 %1RM and 22 to 57 %1RM for peak and mean power) supports the contention that Pmax loads vary between individuals, even within the same subject group. Additionally the insubstantial decreases in power output either side of Pmax load (9.9% and 5.4% peak and mean power respectively) is in concurrence with the concept of Pmax occurring across a 'bandwidth' of loads, rather than one clearly defined point on the load spectrum.

Contraction type and joint angles may also impact on Pmax load. For example, Baker et al. (2001) utilised a similar methodology to the present study except that countermovement free-weight squats were used to a depth of thigh below parallel (approximately $80°$ knee angle) as opposed to the concentric only squats from a $110°$ knee angle in the present study. Pmax load for mean power was reported at 55 - 59 %1RM, although it was noted that loads of 48 – 63 %1RM were very similar in terms of power outputs; slightly higher than the 39.0 ± 8.6 %1RM for mean power output observed in the present study. Although the countermovement should have produced some elastic potentiation (Cronin, McNair, and Marshall, 2001b), the deeper knee angle used by Baker et al. (2001) may have resulted in a slower initial velocity and therefore lower mean power for the concentric phase. It should be noted that Baker et al. (2001) did not measure power output at loads lighter than 40 kg on the bar, so it seems likely that mean power could have been higher at lighter loads using this method of calculation. Whether Pmax differs as a function of contraction type is worthy of further investigation.

Another factor that may impact on Pmax load is the strength level of subjects. It has previously been reported that stronger athletes tend to produce their highest power outputs at a lower %1RM than their weaker counterparts in both upper (Baker, 2001b;

Newton et al., 1997) and lower body (Baker, 2001a; Baker et al., 2001; Sleivert et al., 2004; Stone, Sanborn et al., 2003) exercises. The results of the present study support this contention. The results were very similar when strength was expressed relative to body mass.

Practical applications

Clearly, both Pmax output and the load at which Pmax occurs are affected by technique, training experience, exercise specificity and the method by which power is calculated. Additionally, similar maximum power outputs (mean and peak) appear to occur over a greater range of the load spectrum than commonly perceived. Given the inter-individual differences and insubstantial changes in power output each side of Pmax, the preoccupation of research to identify one load as the training load for maximising mechanical power output would seem problematic. Practitioners may need to regularly monitor individual power outputs in specific exercises and program accordingly, rather than selecting an arbitrary point on the power-load spectrum for all athletes. The prescription of maximal power training should detail the loading parameters specific to each individual exercise, and this should be based on 1RM assessment using the same range of motion, joint angles, and contraction type. Findings from this study may be specific to the standing machine hack-squat-jump only. Practitioners and researchers should be aware that findings may not translate to other common squat derivative exercises, such as the free-weight squat-jump. Furthermore, many sports require the expression of functional power across a range of the power-load spectrum, so the pre-disposition of practitioners choosing one training load may be misplaced. Finally it is unclear whether training at Pmax offers any substantial benefit to functional performance over other training loads, as no research has identified each subjects individual Pmax, trained at that load, and mapped performance changes thereafter. Research should focus on tracking whether or not changes in strength and power parallel changes in functional performance.

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Prelude

Strength and power testing is often used with team-sport athletes, but some measures of strength and power may have limited prognostic/diagnostic value in terms of the physical demands of the sport. Given the apparent assumption amongst strength and conditioning practitioners that power output is a key determinant of explosive functional performance, of specific interest is quantification of the relationship between power outputs and sprint ability. The literature review established that power outputs may be useful determinants of sprint performance although there was considerable variation in the research. In particular, quantification of the relationships between power measures across a full load spectrum and sprint ability is of value to effective training prescription. The review also highlighted that strength measures other than power may be at least as important as power. Hence, this chapter sought to clarify the correlation of power and several kinetic and kinematic measures with sprint ability.

Introduction

A variety of conditioning methods are used to improve speed, one of which is the use of resisted strength training (RST). Of particular interest to many practitioners and researchers in this area is identifying if strength and power outputs (e.g. one repetition maximum, peak power, mean force, etc.) in gym-based exercises such as the squat-jump are related to sprinting ability, which may provide greater insight into those exercises or variables that offer a superior training stimulus in terms of transference of gym-based gains to improving sprint ability. One approach to answering this question is to use correlational analysis, and many researchers have adopted such an approach (Alexander, 1989; Baker et al., 1999a; Chelly et al., 2001; Cronin and Hansen, 2005; Farrar et al., 1987; Hennessy et al., 2001; Kukolj et al., 1999; Wisloff et al., 2004; Young et al., 1995; Young et al., 2002), but the magnitude of the correlations differ markedly between studies, probably due to methodological differences.

First, many different types of dynamometry are used to assess strength and power e.g. isometric (constant angle); isokinetic (constant velocity); and, isoinertial (constant gravitational load) which is also referred to as isotonic (Abernethy et al., 1995). Despite the popularity of isometric and isokinetic tests in research, the general consensus is that they lack face validity due to the large neural and mechanical differences between isometric and isokinetic tests and sprinting (Abernethy et al., 1995; Alexander, 1989; Anderson et al., 1991; Blazevich and Jenkins, 1998; Nesser et al., 1996; Wilson and Murphy, 1996b). Most isoinertial studies have used weight training movements such as the squat or power clean (Baker et al., 1999b; Meckel et al., 1995) or various types of jumps (Hennessy et al., 2001; Mero et al., 1981; Nesser et al., 1996; Wilson et al., 1993) and reported the correlation (r = -0.46 to -0.81) of these activities to acceleration or speed measures. Some researchers have instrumented weight training equipment (e.g. Smith machine) to examine the relationship between muscle force-time characteristics assessed under concentric and/or eccentric contractions and sprint performance (Baker et al., 1999a; Sleivert et al., 2004; Young et al., 1995). This type of approach has resulted in a range of correlations (r = -0.02 to -0.86) depending on the methodologies used.

Second, the type of lift utilised influences the kinetic and kinematic outputs. In traditional weight training lifts where the bar and/or load reaches a velocity of zero at the end of the concentric phase, deceleration occurs for a considerable portion of the contraction. An alternative technique where the load (bar and/or oneself) is projected as in jumping and throwing has been termed 'ballistic' training and can result in higher force outputs (Newton et al., 1994), and would seem to offer a movement pattern that better simulates athletic performance.

Third, the variety of methods used to calculate power outputs also makes comparison between studies difficult. It is thought appropriate to use system mass (inclusion of body mass) to calculate loading intensity during ballistic lower body exercises because the subject must propel themselves and the mass associated with the bar, although there is some conjecture regarding this issue (Dugan et al., 2004; Sleivert et al., 2004). Excluding body mass from the calculation decreases the total mass component, therefore decreasing total force and power outputs.

Fourth, there has been a pre-occupation to investigate only a limited number of kinetic and kinematic variables. Maximal strength and peak power have received much attention, but other variables may be of equal if not more importance. For example, given the impulse-momentum relationship (Enoka, 2002), investigating the relationship between impulse and speed is of particular interest. Additionally, often only a sample of the load spectrum for the RST exercise has been examined to determine the relationship to sprint performance. Various jumps and RST exercises at bodyweight or light loads have been investigated, mainly owing to their perceived contraction force and velocity specificity to sprinting (Baker et al., 1999a; Cronin and Hansen, 2005; Young et al., 1995). However, kinetic variables such as power and impulse may be maximised across a broad range of the load spectrum. For example, it is generally considered that peak power during loaded squat-jumps is maximised at around 20 – 65 %1RM (Baker et al., 2001; Kawamori et al., 2004), hence it is worthwhile investigating a broader spectrum of loads and their relationship to sprinting performance.

Finally, the subject characteristics are also an important aspect of study design. Subjects with little or no experience in RST, or from non-athletic backgrounds, would appear to differ from their more well-trained and/or athletic counterparts in terms of

strength and power capability, and the relationship between these outputs and speed (Harris, Cronin, and Keogh, 2007). Thus, the validity of generalising findings from one subject group to another, such as novice subjects to athletes with experience in RST, is problematic. Additionally, difference between studies in terms of the heterogeneity of the subject group (between-subject standard deviation) contributes to the disparity in the magnitudes of correlations between studies. Cognizant of these limitations, the purpose of this study was to investigate the relationship between sprint ability in well-trained athletes, and the kinetic / kinematic outputs of a machine squat-jump across a range of loads.

Methods

Approach to the problem

To determine the relationship between sprint ability and the kinetics and kinematics associated with squat-jumps across a spectrum of loads a correlational approach was used. Thirty well trained subjects performed machine squat-jumps across loads of 20 to 90 %1RM, and sprints over 10 and 30 or 40 m. Thereafter, Pearson correlations were used to determine the magnitude of the relationships between variables of interest.

Subjects

Thirty male subjects volunteered to participate in this study. The mean ($\pm$ SD) age, mass, and height of the participants were 22.3 $\pm$ 2.8 years, 100.5 $\pm$ 10.6kg, and 181.2 $\pm$ 5.4cm respectively. Seventeen of the subjects were from a National level rugby training squad, and thirteen of the subjects were from a National Rugby League premier squad. All subjects had an extensive resistance training background (4.2 $\pm$ 2.2 yrs). Subjects provided written consent for testing as part of their contractual arrangements with their respective squads and were informed that they could withdraw from the study at any time without prejudice.   The Human Subject Ethics Committee of the AUT University approved all procedures undertaken in this study.

Equipment

Subjects performed their assessments on a customised standing hack-squat machine (Fitness Works, Auckland, NZ) detailed previously (Harris et al., 2007a). The starting position of the sled was adjustable to the nearest 15 mm, allowing lower limb joint angles to be standardised as measured by a goniometer. A linear position transducer (P-80A, Unimeasure, Oregon – mean sensitivity 0.499 mV/V/mm, linearity 0.05 % full scale) was attached to the sled and measured vertical displacement of the sled with an accuracy of 1.0 mm. Data was sampled at 500 Hz and collected via a computer based data acquisition and analysis program (Labview^{TM} 6.1. National Instruments, Austin, Texas).

Sprint times over 10, and 30 or 40 m were measured using the Kinematic Measurement System (KMS, Optimal Kinetics, IN). The KMS timing light system was a single beam modulated visible red-light system with polarizing filters and consisted of three sets of gates. The "start of longest on function" in the KMS software was utilised; therefore the timing of the sprint was initiated at the longest break of the infrared beam. This controlled for the beam being broken more than once by the athlete at the beginning of the sprint and negated the need for a double beam system. The within-trial variability (coefficient of variation ≤ 1.2%) of this procedure has been reported previously (Cronin and Hansen, 2005).

Procedures

The maximal strength (1RM) and concentric power-load spectrum (20-90 %1RM) was assessed for each subject. Instructions were issued to subjects to standardise pre-test preparation (exercise levels, nutrition, etc.) as much as possible in the 24-hour period preceding the testing session. At each session the subjects first performed a standardised warm-up procedure consisting of running, dynamic stretching and ball drills. During the first session, subjects were familiarised with the equipment and procedures by performing two warm-up sets at a light weight (40-60 kg). Two to three trials were then performed to establish 1RM. In an effort to be specific to the knee angles encountered in sprinting (Young et al. 2001), start position was standardised to 110º at the knee using a goniometer (centred at the lateral epicondyle of the knee and aligned to the lateral malleolus and greater trochanter). Adjustable mechanical brakes

were used to fix the stop-start position for the machine at the 110° knee angle. Foot position was self selected by subjects but standardised to within five centimetres between all subjects.

The measurement of force as described in this experiment has been verified by comparison of the linear transducer data with data gathered simultaneously from an accelerometer and a force platform across movement types (concentric only and rebound bench presses - squat, countermovement and drop jumps), loads (40 - 80 %1RM) and sampling frequencies (200-1000 Hz). The data from the linear transducer was shown to be reliable (coefficient of variation (CV) 2.1-8.4%, and intraclass correlation coefficient = 0.92-0.98 for measures of mean and peak force) and valid across these conditions. The reliability of the procedures has been reported previously (Cronin et al., 2004).

In the second session, after the standardised warm-up, a load of 20% of the individual's 1RM was placed on the squat machine and the subjects completed one lift with maximal effort. A one-minute rest period was then allowed before the load was increased to 30% of the individual's 1RM. This process was repeated for loads 30, 40, 50, 60, 70, 80, and 90%, of the individual's 1RM. Subjects were given instructions to move every load with maximal effort and jump if the load permitted. All lifts were commenced from the standardised starting position thus concentric force was measured with no eccentric counter-movement.

Timing lights were placed at the start, 10 and 30 or 40 m in order to collect sprint times over the two distances. Thirteen athletes were assessed over 10 and 30 m, and seventeen athletes were assessed over 10 and 40 m, depending on the sprint testing protocol of the respective sporting organizations. All athletes performed a thorough warm-up as part of their training routine. This included jogging, ball skill drills, dynamic stretching and sub-maximal sprints. The starting position was standardised for all subjects. Athletes started in a two point crouched position with the left toe 30cm back from the starting line and the right toe approximately in line with the heel of the left foot. All assessments were performed on an indoor court surface and subjects wore rubber-soled track shoes.

Data analysis

The hack-squat displacement data were filtered using a low pass, second order, Butterworth filter with a cut-off frequency of 10 Hz. This filtered displacement time data was then differentiated to determine velocity and acceleration. From this data the following variables were calculated from the mass-displacement characteristics of the mass lifted (including body mass) from the start of the upward movement to the peak concentric displacement: mean and peak velocity; mean and peak force; mean and peak power; total work; and total impulse.

Statistics

Means and standard deviations are used throughout as measures of centrality and spread of data. The magnitudes of the relationships were interpreted using Pearson correlation coefficients, which had uncertainty (90% confidence limits) of $\sim\pm0.3$. The magnitudes of the correlation coefficients was interpreted using Cohen's scale (Cohen, 1988): <0.10, trivial; 0.10-0.29, small; 0.30-0.49, moderate; $\geq$0.50, large. An inference about the true (large-sample) value of a correlation was based on uncertainty in its magnitude (Batterham et al., 2006): if the 90% confidence interval overlapped small positive and negative values, the magnitude was deemed unclear; otherwise the magnitude was deemed to be the observed magnitude. The confidence interval was derived via the Fisher z transformation (Fisher, 1921); for trivial-small correlations the confidence limits were $\sim\pm0.3$. Thus the power of this study was such that only correlations greater than >0.2 or <-0.2 were considered clear. Correlations for the 30 and 40 m sprint times were pooled by deriving the back-transformed weighted mean of their Fisher z transforms, where the weighting factor was the inverse of their variances (sample size minus 3).

Results

The kinetic and kinematic outputs of the machine hack-squat at loads of 20 and 90 %1RM may be observed in Table 4.1. Mean sprint times were 1.82 ± 0.07 s, 4.19 ± 0.16 s, and 5.54 ± 0.21 s for 10, 30, and 40 m distances respectively. Mean maximal strength (1RM) was 305 ± 46.6 kg, and relative strength (1RM / kg body-mass) 3.07 ± 0.48 kg/kg body-mass.

Table 4.1. Kinetic and kinematic outputs of the machine hack-squat at loads of 20 and 90 %1RM

	Load (%1RM)	
	20 %1RM	90 %1RM
Peak force (N)	2940 ± 500	4450 ± 550
Mean force (N)	1530 ±150	3660 ± 450
Peak velocity (m.s^{-1})	1.88± 0.21	0.66 ± 0.14
Mean velocity (m.s^{-1})	1.01± 0.10	0.31 ± 0.07
Peak power (W)	4520±1070	2640 ± 590
Mean power (W)	1600 ±230	1140 ± 270
Work (N.m)	1260 ±460	1800 ± 850
Impulse (N.s)	800 ±120	3410 ± 800

The inter-correlation matrix for strength measures and sprint times are detailed in Table 4.2. Body-mass was moderately correlated to 10 m sprint time and strongly correlated to 30/40 m sprint time. Strength, as described by a subject's 1RM was only trivially correlated to sprint times at either distance, but 1RM expressed relative to body-mass (1RM rel) was moderately negatively correlated to 10-m sprint time. Sprint times for 10 m and 30/40 m were correlated nearly perfectly.

Table 4.2. Inter-correlation matrix for strength measures and sprint times

	10-m sprint time	30/40-m sprint time	1RM	Mass	1RM rel
10-m sprint time	1.00				
30/40-m sprint time	0.87††	1.00			
1RM	0.20	-0.14	1.00		
Mass	0.40†	0.64††	0.32†	1.00	
1RM rel	-0.10	-0.33†	0.75††	-0.39†	1.00

10-m sprint time = sprint time 10m; 30/40-m sprint time = sprint time 30 or 40 m; 1RM = Machine squat 1RM; Mass = Body-mass (kg); 1RM rel = Machine squat 1RM relative to body-mass.

†Clear moderate correlation
††Clear strong correlation

The relationship between kinetic and kinematic measures across a spectrum of loads, and sprint times can be observed in Figure 4.1. Values were generally positive and of clear moderate to strong magnitude ($r = 0.32$ to 0.53). For example, peak velocity ($r = 0.41$ to 0.32), and mean force ($r = 0.45$ to 0.33) at loads from 20 to 50 %1RM. A similar pattern was observed for mean velocity, peak power and peak force. Most other correlations were classified as trivial to small. Work was the only negative correlation (10 m sprint time) across all loads, although the magnitude of the correlation was small ($r = -0.18$ to -0.26).

The relationship between kinetic measures across a spectrum of loads expressed relative to body mass and sprint times may be observed in Figure 4.2. Peak and mean velocity are not reported as it is not valid to express velocity relative to body mass. Values were generally positive and of trivial to small magnitude ($r = 0.01$ to 0.29). For example, mean power/kg ($r = -0.06$ to 0.30), and peak force/kg ($r = -0.03$ to 0.28). Work/kg and impulse/kg were of clear moderate negative correlation to 10 m sprint time ($r = -0.2$ to -0.39) across most loads. Mean force/kg ($r = -0.32$ to -0.40), and impulse/kg body-mass ($r = -0.31$ to -0.47) were of clear moderate negative magnitude to 30/40 m sprint time.

Figure 4.1. Correlation coefficients between sprint times and kinetic / kinematic variables. Shading indicates trivial correlations.
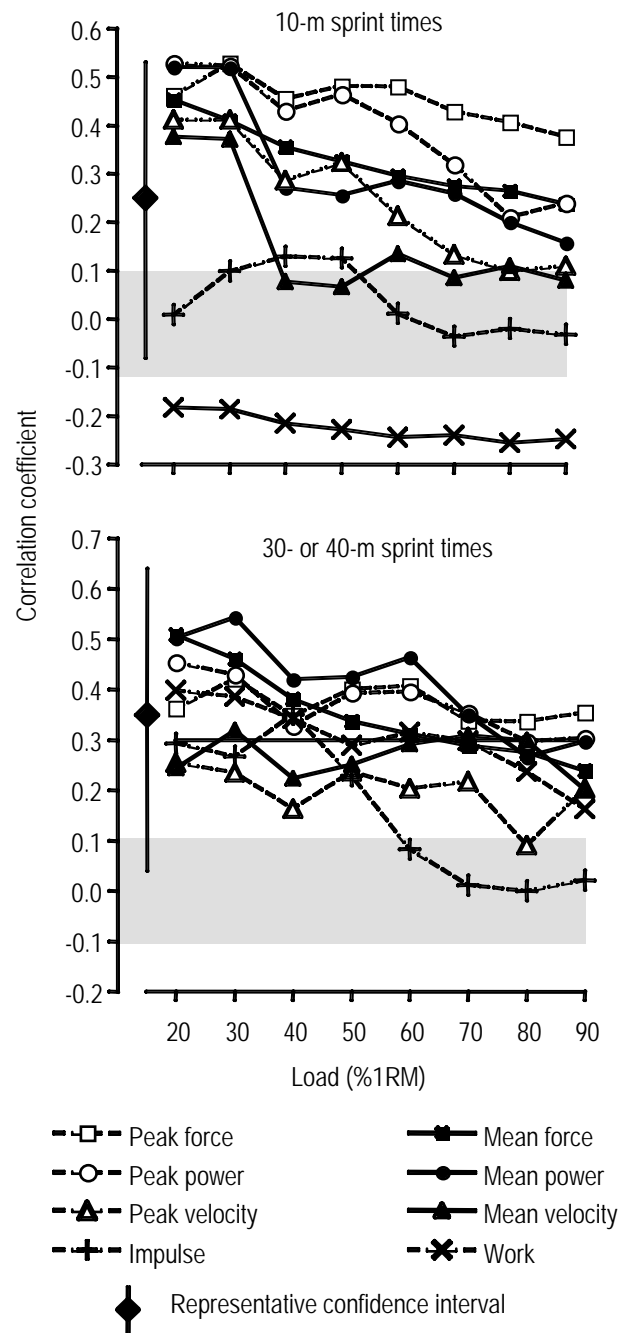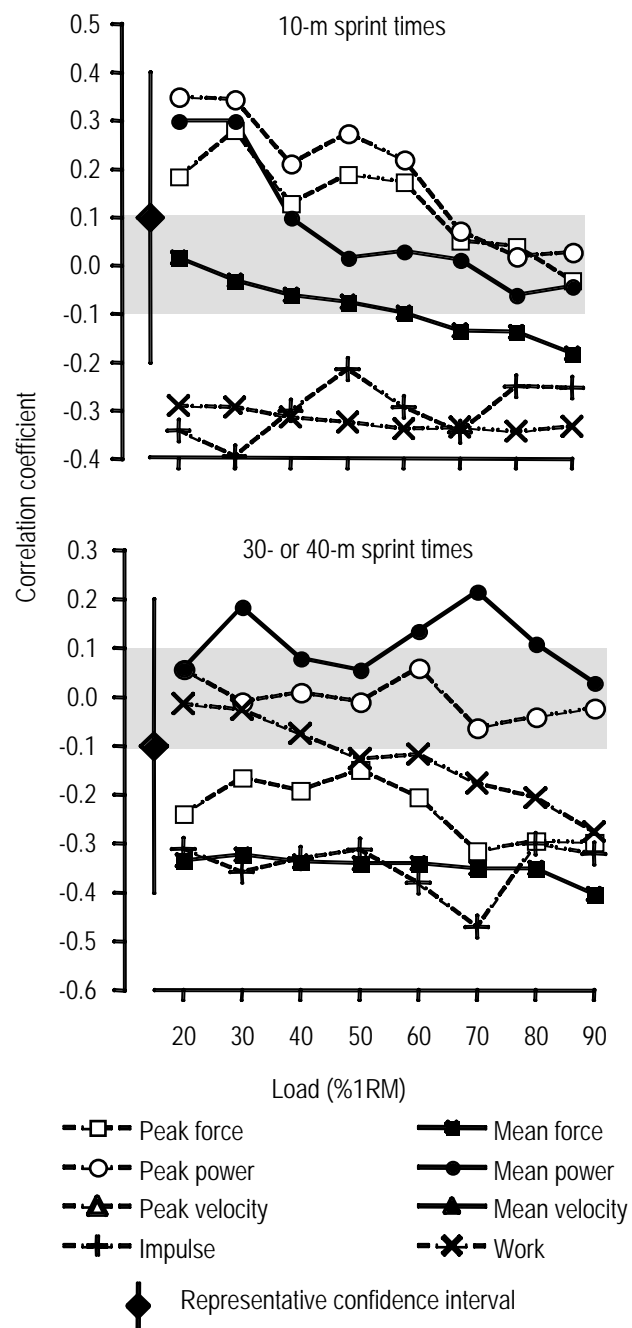
Figure 4.2. Correlation coefficients between sprint times and kinetic / kinematic variables expressed relative to body-mass. Shading indicates trivial correlations.

Discussion

The sprint times observed in the present study were similar to other studies using well-trained rugby and rugby league athletes (Baker et al., 1999a; Cronin and Hansen, 2005; Nesser et al., 1996). Maximal strength was considerably higher than reported in other similar research, probably attributable to the higher starting position (110° knee angle) of the squat used in this study, enabling a more forceful movement due to an advantageous length-tension relationship in the knee and hip extensors (Hay, 1992). Clearly, the subjects in the present study were a well-trained sample and as fast and strong as other similar athletes. Of interest therefore, acknowledging the training status of the athletes used in this study and the methodological limitations cited previously, was establishing whether any of the kinematic and/or kinetic variables assessed using a machine squat-jump across a spectrum of loads were clearly correlated to sprint ability.

Sprint ability over short distances (under 10 m) and longer distances (over 30 m) are considered by many researchers and practitioners to require separate and specific strength qualities and therefore training techniques (Delecluse et al., 1995; Young et al. 2001). It is generally considered that shorter sprints require greater contributions of concentric muscle contractions and knee extensor activity versus longer sprints that are characterised by greater stretch shortening cycle (SSC) and hip extensor activity (Young et al., 2001). However, reported correlations between sprint times over different distances (Baker et al., 1999a; Cronin and Hansen, 2005; Nesser et al., 1996; Young et al., 1995) are typically very strong ($r = 0.72$ to 0.99). The correlation between 10 m and 30/40 m sprint times in the present study was similar to those cited in previous studies ($r = 0.87$). It would appear that the indices of acceleration and maximal sports speed for this sample share a great deal of common variance ($> 75\%$) in this sample and the preoccupation of researchers and practitioners to treat and train these variables as separate qualities possibly over-emphasised (Young et al. 2001).

Maximal strength is perceived to be an underpinning neuromuscular quality for athletic performance (Schmidtbleicher, 1985; Stone et al., 2002), however considerable investigation into the relationship between maximal strength and sprinting ability provides the antithesis of such a contention. For example, Baker and Nance (1999a)

found trivial to small non-significant relationships between 3RM squat strength and 10 m (r = -0.06) or 40 m (r = -0.19) sprint times of professional rugby league players. Several other studies (Costill et al., 1968; Cronin and Hansen, 2005; Hasegawa, 2004) have reported very low correlations between maximal strength and sprint measures (r = -0.01 to r = 0.30), which are supported by the results of the present study. Strength, as assessed by 1RM was only trivially correlated to sprint times at either distance (r = 0.20 and r = -0.14 for 10 m sprint time and 30/40 m sprint time respectively). It is reasonable to assume that larger athletes would be stronger, but also sprint slower due to the inertia associated with greater body mass, particularly in the early stages of the sprint. The clear moderate correlation between body mass and 10 m sprint time (r = 0.40) supports this assertion. However, conjecture remains as other researchers (Wisloff et al., 2004), have reported a near perfect correlation between squat 1RM and 10 m sprint time (r = 0.94), and a very strong positive correlation between 1RM and 30 m sprint time (r = 0.71) in male soccer players.

It might be expected that strength expressed relative to body mass would be more strongly related to sprint ability. It has also been proposed that the concentric strength measures should be better related to starting ability due to this phase having a higher concentric component as compared to later in the sprint (Young et al. 2001). Our results support this notion in terms of the importance of relative strength, although somewhat unexpectedly the correlation between 1RM rel and 10 m sprint time was weaker (r = -0.10) than the clear moderate value observed between 1RM rel and 30/40 m sprint time (r = -0.33). A similar result was reported by Cronin and Hansen (2005) (r = -0.01 and r = -0.29 for 10 m sprint time and 30 m sprint time respectively), but these values and ours are much lower than reported in some other similar research. For example, Baker and Nance (1999a) found that squat strength expressed relative to body mass was strongly related to 40 m sprint time of rugby league athletes (r = -0.66), and Meckel et al. (1995) reported relative squat strength to correlate highly (r = -0.88) with 100 m sprint times. Both studies utilised squatting movements that incorporated some SSC activity, conceivably more specific to top speed sprinting, possibly explaining the stronger correlations. Notably, Baker and Nance (1999a) observed a much lower correlation between squat strength/kg and 10 m sprint time (r = -0.39) supportive of our contention, although SSC activity is not exclusive to top speed sprinting.

Interestingly, the only measure of force negatively correlated to sprint time in the present study was mean force relative to body mass and 30/40 m sprint time (r = -0.32 to -0.40) across all loads. Young et al. (1995) also investigated the relationship between force measures (concentric only Smith squat-jump with a 19kg bar load from 120° knee angle) and sprinting performance of 20 elite junior track and field athletes (11 males and 9 females). There was no mention whether the pooling of the male and female subjects were investigated for bi-modal distribution (by gender), which can result in artificially high correlations, therefore the magnitude of the correlations need to be interpreted with caution. The best predictors of starting performance (time to 2.5 m) included force relative to body weight generated after 100 ms (F100/wt) from the start of the concentric jump movement (r = -0.73), and maximum force (r = -0.72). The best predictors of maximum sprinting speed included F100/wt (r = -0.80) and maximum force (r = -0.79). Using a similar methodology Wilson et al. (1995) found the force at 30 ms in a concentric squat-jump was significantly correlated to sprint performance (r = -0.62) and able to effectively discriminate between good and poor performers. The results of Wilson et al. (1995) and Young et al. (1995) support the concept that, because sprinting involves efforts of short duration, strength qualities such as the rate of force development or force applied at 100 ms may be more important than maximal strength.

Mechanical power output has attracted a great deal of attention in the research and conditioning fraternity in an attempt to clarify its relationship to functional performance (Baker et al., 1999a, 1999b; Kukolj et al., 1999; Meckel et al., 1995; Sleivert et al., 2004; Thomas et al., 1996; Young et al., 1995; Young et al., 2002). However, disentangling the findings is challenging due to discrepancies in research design, terminologies and methods for calculation of power. We observed a clear strong positive correlation between mean and peak power and sprint times at both distances, most probably explained by the fact that the larger athletes produced greater force outputs, but were also slower due to greater body mass. Of particular interest is that no clear negative correlations were found between mean or peak power at either of the sprint distance times, even when power was expressed relative to body mass. Indeed, correlations were mostly positive across the entire load spectrum. These findings are in direct contrast to those of Sleivert and Taingahue (2004) who investigated the relationship between 5 m sprint times and power variables in trained athletes from rugby, rugby league and basketball with an average of 2.4 years of RST experience.

Average and peak powers were assessed over 30-70 %1RM of concentric only traditional squats and split squats performed in a ballistic manner. Notably, both average and peak power relative to body mass were strongly negatively correlated to 5 m sprint time ($r = -0.64$ to -0.68). The authors chose not to incorporate body mass (so-called system mass) into the equation for force, asserting that it is not strictly mechanically correct to do so. Sleivert and Taingahue (2004) noted that not using system mass has the effect of markedly reducing power outputs and altering the point on the power-load spectrum where maximal power output occurred. It is conceivable that excluding system mass may also influence correlational analysis between power variables and sprint times, however it seems unlikely that it would exclusively account for the difference in the magnitude of the correlations between the present study and that of Sleivert and Taingahue (2004). Similarly, Baker and Nance (1999a) also found strong relationships between relative average power outputs of loaded (40–100 kg) counter movement jump-squats and sprint times over 10 m ($r = -0.52$ to -0.61) and 40 m ($r = -0.52$ to -0.76). It is not clear from their methodology whether system mass was utilised.

A key finding in the present study was that impulse expressed relative to body-mass was clearly correlated to 30/40 m sprint time across all loads, and to 10 m sprint time at 20 and 30 %1RM ($r = -0.31$ to -0.47). Given the impulse-momentum relationship, impulse is theoretically an important determinant of sprint ability as indicated by biomechanists reporting the determinants of speed via qualitative models (Hay, 1992). This variable therefore should be of greater interest to the strength and conditioning fraternity, however, impulse has received little attention in the research on predictors of speed. Wilson et al. (1995) investigated the relationship between impulse developed in the first 100ms of a concentric Smith squat-jump (unloaded) from 110° (imp110) and 150° (imp150) knee angles, and sprinting ability over 30 m. Although reported as non-significant, they reported a moderate correlation ($r = -0.49$) between imp150 and sprint ability. Interestingly, the relationship between imp110 and sprint ability was trivial ($r = 0.06$). Young et al. (1995) also investigated the relationship between impulse at 100ms in a squat-jump and sprint times but the correlation was not reported. Another little reported variable of interest is total work done. We observed negative correlations between work and 10 m sprint time ($r = -0.18$ to -0.34), and when expressed relative to body mass, 30/40 m sprint time ($r = -0.01$ to -0.28). Perhaps impulse and work are

important strength qualities to develop in the pursuit of enhanced sprint performance. Further research is needed into the relationship of these strength measures to functional performance.

Practical applications

The reader needs to be cognizant of the following limitations when interpreting the results of this study. First, the resistance exercise (machine hack-squat) utilised a purely bi-lateral, a-cyclical, vertical expression of force. Although it is common conditioning practice to use squat-jumps and derivatives, it has been postulated that a more specific training method for speed would use horizontal force production in unilateral movements, such as loaded sled towing (Zafeiridis et al., 2005). Indeed, biomechanical similarity of assessment dynamometry to the functional performance task is a fundamental tenet of correlational analyses. However, given the propensity of conditioning practitioners to use squats and derivatives as a key exercise in resistance training programs, investigation of this exercise would appear logical. Second, the strength and power variables were assessed over the concentric phase of the movement only. Thus, no measures of eccentric force contribution, or SSC activity were assessed. Also, the kinetic and kinematic variables were assessed over the entire contraction whereas force production during sprinting occurs in a very short duration (Tidow, 1990). Finally, only single repetitions were performed at each load. Typically, training involves multiple repeated repetitions; kinetic and kinematic outputs may differ between multiple and single repetitions (Harris, Cronin, and Keogh, 2007). It is however worthwhile investigating single repetitions allowing for the methodological issues discussed previously. It should be noted that correlations can only give insights into associations and not into cause and effect, therefore longitudinal training studies are needed to provide valid information regarding possible superior training stimuli. Additionally, homogeneity of our subject group may account for some of the disparity between our correlations and those of other researchers. The practical applications described herewith need to be interpreted with this in mind.

The purpose of this study was to establish whether any kinetic or kinematic variables were related to sprint ability over 10 and 30 or 40 m. If a clear strong relationship was found it may provide greater insight into better variables to monitor and develop for improved sprint ability. The fact that neither mean nor peak power was negatively

correlated to sprint times suggests that the preoccupation with maximizing power output in machine squat-jumps to improve sprint ability is misplaced. Variables such as impulse and work are potentially more useful. However, it is most likely that the bi-lateral, vertical, a-cyclical resistance exercise used in this study lacked biomechanical specificity to sprinting performance. Research needs to monitor the changes in kinematics and kinetics of an exercise, and sprint times over a training intervention to better understand those variables/exercises that may improve sprint ability.

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CHAPTER 5. INTER-RELATIONSHIPS BETWEEN MACHINE SQUAT-JUMP STRENGTH, FORCE, POWER AND 10 M SPRINT TIMES IN TRAINED SPORTSMEN

Prelude

Strength and conditioning practitioners appear focussed on developing maximal strength based on the premise that it underpins explosive muscular performance. Investigation into the relationship between strength and a multitude of explosive power measures is limited though. Furthermore, the relationship of explosive force and power with functional performance is unclear. Following the previous two chapters, it was proposed that explosive power measures may be more important determinants of sprint performance than the so-called traditional measures such as peak power, given that they describe more sprint specific portions of the force-time and power-time curves. Some research provides support for such a proposition although methodological differences once again limit the ability to draw conclusions. Specifically, explication of the following areas was needed: 1) Are higher maximal strength levels related to higher explosive power outputs? 2) How does this relationship differ at opposite ends of the load spectrum? 3) Do the multitude of explosive power measures describe different neuromuscular qualities? Initial investigation determined high intercorrelations between certain groups of explosive power measures, hence these groupings were used in further statistical analyses for interrelationships and relationships to sprint performance. It was considered that such an investigation would provide insight into which strength and power measures should be examined over the course of a subsequent training study.

Introduction

Power is the product of force and velocity hence many practitioners misguidedly underpin their conditioning practice on the theoretical supposition that increasing force production through maximal strength training will positively influence power outputs and therefore explosive functional performance (Schmidtbleicher, 1985; Stone et al., 2002). However, the influence maximal strength has on power production is dependent on the magnitude of the load (Cronin et al., 2000; Moss et al., 1997; Schmidtbleicher, 1992) but further investigation is warranted to substantiate this. That is, it is unclear from research if athletes exhibit higher levels of maximal strength do they also produce higher power outputs across a spectrum of loads?

With regard to representing force and power outputs, these measures are typically expressed as either peak (instantaneous) or mean (average of sample points across a contraction) values for a particular movement, although even the term 'maximal power output' has been represented ambiguously (Baker et al., 1999b). A range of so-called "explosive" measures can also be used to describe outputs from distinctive portions of the force-time and power-time curves. For example, Zatsiorsky (2006) used terms such as the index of explosive strength, reactivity coefficient, S-gradient, and A-gradient to describe rate of force development. The index of explosive strength refers to the ability to exert maximal forces in minimal time. The reactivity coefficient expresses the index of explosive strength relative to body mass and is reportedly highly correlated to jumping performance (Zatsiorsky et al., 2006). The S-gradient characterises the rate of force development at the beginning phase of muscular effort whereas the A-gradient quantifies rate of force development in the late stages of muscular effort (Zatsiorsky et al., 2006). Apart from these descriptions and the actual formulae themselves, Zatsiorsky's treatise of these strength qualities is limited and a detailed analysis of how the measures relate to traditional measures of force, and how they inter-relate has to the knowledge of these authors not yet been reported.

It is generally considered that sprinting requires force to be produced within a 100-250 ms ground contact time (Mann et al., 1980; Tidow, 1990), thus it has been proposed that explosive force measures such as rate of force development in strength training (Schmidtbleicher, 1992) may be more important to sprint performance than the so-

called traditional measures such as peak power. Research supports such a proposition to some extent (Abernethy et al., 1995; Wilson et al., 1995; Young et al., 1995). For instance, Wilson et al. (1995) investigated the relationship of twenty force-time variables during an unloaded Smith machine squat-jump to sprinting performance. Only the concentric force at 30 ms was significantly correlated to sprint performance (r = -0.62) and able to effectively discriminate between good and poor performers. Moderate (non-significant) correlations were also reported for rate of force development (r = -0.45) and impulse at 100 ms (r = -0.49) with sprint performance. Young et al. (1995) using a similar methodology found that the best single correlate of maximum running speed was the force applied at 100ms (relative to body weight) during a concentric jump (r = -0.80). Thus, it would seem that different portions of the force-time curve may better predict performance than using more traditional measures such as a peak force or power output. It is unknown whether Zatsiorsky's measures relate to sprinting ability as only one study has reported the correlations between Zatsiorsky's measures and functional (lunge) performance (Cronin, McNair, and Marshall, 2003). Given the paucity of research in this area there is a need to elucidate whether or not the traditional explosive and Zatsiorsky measures are related to functional performance and hence of prognostic and diagnostic value.

A detailed analysis of the influence of maximal strength on explosive force and power, and the inter-relationships between explosive strength measures and sprint ability would be of great value to the provision of valid strength assessment and programming. Therefore, the purposes of this study were to examine the inter-relationships between maximal strength, traditional, explosive, and Zatsiorsky's measures of force and power at different loads and how they relate to 10-m sprinting ability in well-trained sportsmen.

Methods

Subjects

Forty elite-level rugby and rugby-league players volunteered and provided written consent for testing as part of their contractual arrangements with their squad. Their age, mass and height were 21.4 ± 3.2 yrs, 99.8 ± 9.6 kg, and 182.2 ± 6.3 cm (mean ± SD).

All had experience of resistance training (4.2 ± 2.2 y). The AUT University institutional ethics committee approved all procedures.

Equipment

Subjects performed their assessments on a customised standing hack-squat machine (Fitness Works, Auckland, NZ) with a linear position transducer (P-80A, Unimeasure, Oregon – mean sensitivity 0.499 mV/V/mm, linearity 0.05 % full scale) attached to the sled as described in detail previously (Harris et al., 2007a). Sprint times over 10 metres were measured using the Kinematic Measurement System (KMS, Optimal Kinetics, IN), also detailed previously (Harris et al., 2008).

Procedures

Sprint times (10 m) were first assessed after the procedures detailed previously (Harris et al., 2008). After a 10-minute rest period, the concentric maximal strength (1RM) and kinetic and kinematic outputs at 20 %1RM and 80 %1RM were measured. The loads were chosen because 20 %1RM had previously been established as the approximate load where peak power output occurred in a similar subject group (Harris et al., 2007a) and because 80 %1RM is typically prescribed for maximal strength style training. Thus it was considered the two loads represented two different styles of training and were sufficiently contrasted to allow an analysis of load-effect on the variables of interest. The procedures for the 1RM strength testing has been detailed previously (Harris et al., 2008), and in previous chapters. After a standardised rest period, a load of 20% of the individual's 1RM was placed on the squat machine and the subjects completed one lift with maximal effort. A 1-minute rest period was then allowed before the load was increased to 80% of the individual's 1RM. Subjects were given instructions to move every load with maximal effort and jump if the load permitted. All lifts were commenced from the standardised starting position thus the movement was concentric only.

Data analysis

The hack-squat displacement data from the start of the upward movement to the peak concentric displacement were filtered using a low pass, second order, Butterworth filter

with a cut-off frequency of 10 Hz. This filtered displacement time data were then differentiated to determine velocity and acceleration. From this data the following traditional measures were calculated from the mass-displacement characteristics of the mass lifted (including body mass) from the start of the upward movement to the peak concentric displacement: peak force and peak power per kg body mass. So-called explosive measures of force calculated were: maximal rate of force development per kg body mass; impulse at 200 ms per kg body mass; and, rate of force development at 200 ms per kg body mass. The 200 ms measures were chosen owing to their theoretical specificity to the ground contact time exhibited in short sprints (Mann et al., 1980; Mero, 1988; Young et al., 1995). Additionally, measures of explosive force according to the formulae of Zatsiorsky (2006) calculated were the reactivity coefficient (peak force / [time to peak force x body mass]) and starting gradient (50% peak force / time to 50 % peak force) expressed relative to body mass. All explosive and Zatsiorsky's measures were calculated for power in the manner described for the force measures (except impulse at 200 ms).

Statistics

Means and standard deviations are used throughout as measures of centrality and spread of data. Pearson correlation coefficients were used to determine the magnitude of the relationships between and within the following functional groups of kinetic measures:

Traditional force measures: Peak force

Traditional power measures: Peak power

Explosive force measures: Rate of force development at 200ms; maximum rate of force development; and impulse at 200ms

Zatsiorsky's force measures: Reactivity coefficient and S-gradient

Explosive power measures: Rate of power development at 200ms and maximum rate of power development

Zatsiorsky's power measures: Reactivity coefficient (power) and S-gradient (power)

All measures were expressed relative to body mass except the reactivity coefficient which was implicitly corrected for body mass. To justify the functional groupings as

above we first investigated mean correlations between variables within the groups and determined they were at least very high (>0.70).

The magnitudes of correlations were described as trivial (0.0-0.1), low (0.1-0.3), moderate (0.3-0.5), high (0.5-0.7), very high (0.7-0.9), or practically perfect (0.9-1.0) (Cohen, 1988; Hopkins, 2002). An inference about the true (large-sample) value of a correlation was based on uncertainty in its magnitude (Batterham et al., 2006); if the 90% confidence limits overlapped substantial positive and negative values, the magnitude was deemed unclear, otherwise the magnitude was deemed to be the observed magnitude. Confidence limits for the mean of clusters of correlations and for the comparisons of the means were derived by bootstrapping using 6000 re-samples. For trivial-small correlations the confidence limits were ~±0.25; thus the power of this study was such that only correlations greater than >0.15 or <-0.15 were considered clear.

Results

Mean 10-m sprint time, maximal strength (1RM) and relative strength (1RM per kg body mass) were 1.79 ± 0.06 s, 303 ± 43 kg, and 3.08 ± 0.51 kg per kg body mass respectively. Descriptive statistics for kinetic outputs of the machine jump-squat (all relative to body mass) at 20 %1RM and 80 %1RM are detailed in Table 5.1. Relative peak force and relative impulse at 200 ms were clearly greater at 80 %1RM than 20 %1RM. However, the magnitude of all other variables can be observed to be greater for the 20 %1RM load.

Table 5.1. Descriptive statistics for kinetic outputs during a machine jump-squat at 20 and 80 %1RM (all relative to body-mass)

	20 %1RM Mean ± SD	80 %1RM Mean ± SD
Peak force (N kg^{-1})	30 ± 5	42 ± 6
Peak power (W kg^{-1})	47 ± 10	29 ± 7
Rate of force development at 200ms (N· s^{-1}.kg^{-1})	60 ± 21	18 ± 13
Maximum rate of force development (N· s^{-1}.kg^{-1})	77 ± 60	23 ± 20
Impulse at 200ms (N.s kg^{-1})	4.9 ± 0.8	7.4 ± 0.9
Reactivity coefficient	79 ± 62	23 ± 19
Starting gradient	125 ± 65	38 ± 28

The correlations between 1RM, peak force and peak power, with the explosive / Zatsiorsky measures (all per kg body mass) at 20 %1RM and 80 %1RM are presented in Table 5.2. Relative strength was clearly correlated with all explosive / Zatsiorsky measures with small to moderate magnitudes ($r = 0.27$ to 0.43) except for Zatsiorsky's force measures at 80 %1RM ($r = 0.00$). At 20 %1RM both relative peak force and power were highly or very highly correlated with all explosive / Zatsiorsky measures ($r = 0.54$ to 0.89). At 80 %1RM relative peak force and peak power were highly correlated with the explosive / Zatsiorsky power measures ($r = 0.42$ to 0.55) but were not clearly correlated with any of the force measures ($r = 0.08$ to 0.25). The correlations between relative peak force and power with all explosive / Zatsiorsky measures at 80 %1RM were clearly lower than at 20 %1RM.

The intercorrelations between explosive and Zatsiorsky measures (all relative to body mass) at 20 %1RM and 80 %1RM are shown in Table 5.3. Values were all clear and at least of moderate magnitude, but mostly very high or practically perfect ($r = 0.45$ to 0.97). The magnitude of the intercorrelations at 20 %1RM were all higher than at 80 %1RM, almost all clearly.

Table 5.2. Correlations (±approximate 90% confidence limits) between relative strength, peak force and peak power, and the explosive / Zatsiorsky measures at 20 and 80 %1RM during a machine jump-squat (all relative to body-mass)

	1RM per kg body-mass	Peak force per kg body-mass	Peak power per kg body-mass
20 %1RM			
Explosive force measures	0.43; ±0.22	0.70; ±0.12	0.71; ±0.09
Zatsiorsky's force measures	0.30; ±0.30	0.66; ±0.13	0.54; ±0.13
Explosive power measures	0.36; ±0.22	0.86; ±0.06	0.86; ±0.07
Zatsiorsky's power measures	0.38; ±0.25	0.89; ±0.05	0.88; ±0.06
80 %1RM			
Explosive force measures	0.35; ±0.25	0.25; ±0.18	0.09; ±0.28
Zatsiorsky's force measures	0.00; ±0.29	0.22; ±0.20	0.08; ±0.26
Explosive power measures	0.28; ±0.24	0.50; ±0.15	0.42; ±0.25
Zatsiorsky's power measures	0.27; ±0.24	0.53; ±0.15	0.55; ±0.26

Explosive force measures = rate of force development at 200ms, maximum rate of force development, and impulse at 200ms; Zatsiorsky's force measures = reactivity coefficient and S-gradient; Explosive power measures = rate of power development at 200ms and maximum rate of power development; Zatsiorsky's power measures = reactivity coefficient (power) and S-gradient (power).

Table 5.3. Inter-correlation between kinetic measures (relative to body-mass) at 20 and 80 %1RM during a machine jump-squat (±approximate 90% confidence intervals)

	Explosive force measures	Zatsiorsky's force measures	Explosive power measures	Zatsiorsky's power measures
20 %1RM				
Explosive force measures	0.68; ±0.13			
Zatsiorsky's force measures	0.76; ±0.08	0.88; ±0.07		
Explosive power measures	0.83; ±0.07	0.76; ±0.08	0.94; ±0.05	
Zatsiorsky's power measures	0.82; ±0.06	0.76; ±0.08	0.96; ±0.02	0.97; ±0.01
80 %1RM				
Explosive force measures	0.53; ±0.15			
Zatsiorsky's force measures	0.55; ±0.14	0.47; ±0.28		
Explosive power measures	0.56; ±0.12	0.56; ±0.14	0.67; ±0.15	
Zatsiorsky's power measures	0.53; ±0.13	0.45; ±0.25	0.84; ±0.08	0.83; ±0.14

Explosive force measures = rate of force development at 200ms, maximum rate of force development, and impulse at 200ms; Zatsiorsky's force measures = reactivity coefficient and S-gradient; Explosive power measures = rate of power development at 200ms and maximum rate of power development; Zatsiorsky's power measures = reactivity coefficient (power) and S-gradient (power).

The correlations between 10-m sprint time with all of the explosive / Zatsiorsky measures at either load were found to be trivial (r = -0.01 to 0.06 ±0.20 approximate 90% confidence limits). Relative strength was highly correlated with relative peak force at 20 %1RM (r = 0.65; ±approximate 90% confidence limits 0.16) and practically perfectly correlated at 80 %1RM (r = 0.91; ±0.05). The magnitude of the correlations between relative strength and relative peak power were lower (r = 0.32; ±0.20 and -0.03; ±0.28 at 20 %1RM and 80 %1RM respectively) and clearly different. Relative strength and peak velocity were not clearly correlated at 20 %1RM (r = -0.18; ±0.21) but their relationship at 80 %1RM (r = -0.46; ±0.18) was clearly stronger. Relative peak force was very highly correlated with relative peak power at 20 %1RM (0.87; ±0.11) but their relationship was clearly weaker at 80 %1RM (0.25; ±0.16).

Discussion

A key finding of this study was that the relationship between maximal strength and traditional peak power (r = 0.32 and -0.03 at 20 %1RM and 80 %1RM respectively) was lower than might be anticipated based on previous research (Baker et al., 1999b; Bemben and McCalip, 1999; Cronin et al., 2003; Mastropaolo, 1992; Moss et al., 1997; Peterson, 2006; Stone, Sanborn et al., 2003; Stone, O'Bryant et al., 2003). Methodological discrepancies limit our ability to make inter-study comparisons, as outlined in previous reviews (Abernethy et al., 1995; Cronin and Sleivert, 2005; Harris, Cronin, and Keogh, 2007), but briefly they include: the type of exercise used for testing and/or training; the method of calculating and reporting of force and power outputs; the subject group; and vagaries in statistical reporting. Results from studies that have used a combination of methods similar to those of the present study should allow for a more direct comparison of findings. For example, Cronin et al. (2003) reported a very strong correlation (r = 0.83) between 1RM and peak power at 50 %1RM on a supine squat machine in 31 athletic males. Stone et al. (2003) also reported very strong correlations between 1RM and peak power output during counter-movement (to 90° knee angle) and concentric squat-jumps at loads of 10 to 90 %1RM (r = 0.74 to 0.94), although it was noted that the range of subjects' squat training experience and strength were purposely chosen to highlight associations between strength and power. In contrast, Asci and Acikada (2007) observed practically no relationship (r = 0.08) between bench press 1RM and maximum power output measured during a non-release explosive bench press

at loads of 40 to 80 %1RM in 56 male athletes. The comparative homogeneity of our subjects' strength possibly reduced the magnitude of our correlations, as suggested by Peterson (2006) about studies using small select groups of highly trained athletes. Consequently, maximal strength in our group of well-trained athletes provides limited practically useful indication of adaptive association to peak power output.

Schmidtbleicher (1992) postulated that maximal strength is the basic quality affecting power output, but that its effects on power diminish as the external load decreases. Our findings oppose such assertions; the relationship we observed between strength and power was weaker at 80 %1RM than at 20 %1RM. Considering the clearly stronger and negative correlation between relative strength and peak velocity at 80 %1RM than 20 %1RM and the clearly weaker correlation between relative peak power and relative peak force at 80 %1RM, it seems that the ability to produce high power outputs relative to body mass at heavier external loads is influenced more by the ability to move the load at velocity rather than to produce high forces. It may be that there should be less preoccupation with increasing the load lifted and greater focus on moving set loads at greater velocity in the development of speed in athletes. If this is the case, it is recommended that strength and conditioning practitioners should identify how different interventions affect the force-velocity-load spectrum or at least monitor the velocity changes of set loads.

The correlations we observed for relative strength with explosive and Zatsiorsky measures of force were generally moderate and thus weaker than previous findings. Cronin et al. (2003) examined the relationship between unilateral, concentric only 1RM and a range of force and power variables at 50 %1RM on a customised supine squat apparatus. Maximal strength was practically perfectly correlated to impulse at 100 ms ($r = 0.94$), highly correlated to Zatsiorsky's reactivity coefficient ($r = 0.56$), and very highly correlated to Zatsiorsky's index of explosive strength ($r = 0.81$). It is possible that the lower correlations we observed here were at least in part because we chose to report all force and power variables relative to body mass. The weaker correlation observed by Cronin et al. (2003) for maximal strength with Zatsiorsky's reactivity coefficient (which is simply the index of explosive strength relative to body mass) versus Zatsiorsky's index of explosive strength provides some support for such a proposition.

The correlations of traditional peak force and power with all of the explosive and Zatsiorsky measures were clearly lower at 80 %1RM than at 20 %1RM. This apparent discrepancy may be due to the characteristics of the force-time curves at differing loads. Kawamori et al. (2006) reported that time to peak force during a dynamic mid-thigh clean pull was significantly slower at 90 %1RM (255 ms) than at 30 %1RM (152 ms). A similar pattern was evident for time to peak rate of force development (157 ms and 100 ms for 90 %1RM and 30 %1RM respectively). Haff et al. (1997) also reported a general trend for weaker correlations between rate of force development in a dynamic mid-thigh pull with peak force in a concentric only squat-jump as the load of the mid-thigh pull increased, although low sample size ($n = 8$) limited statistical power. These findings provide some indication that, with increasing external load, there is a divergence in the times to traditional peak force and explosive force measures. Further analysis of the force-time and power-time curves of dynamic lifts at different loads for time to peaks and inter-correlation of strength variables would be worthwhile.

The explosive power measures used in this study (reactivity coefficient and S-Gradient using power instead of force) included a hybrid of Zatsiorsky's explosive force measures. To the knowledge of these authors this is the first study to explore the power-time curve in this manner. The inter-relationships between Zatsiorsky's power measures at either load were very high to practically perfect ($r = 0.97$ and 0.83 at 20 and 80 %1RM respectively). Given the clear inter-relationship between these variables, it would appear that either should provide ostensibly similar information for assessment and programming of power capability in the early phases of contraction.

Although it is acknowledged that correlations do not imply cause and effect, our findings indicate that explosive force measures of a machine squat-jump are not usefully associated with sprint ability. Contrary to previous reports (Wilson et al., 1995; Young et al., 1995), we found practically no relationship between any of the explosive measures and 10-m sprint ability. Wilson et al. (1995) investigated the correlations between impulse developed in the first 100 ms of a concentric Smith squat-jump (unloaded) from 110° and 150° knee angles, and sprinting ability over 30 m. A moderate correlation ($r = -0.49$) was noted for the 150° knee angle squat-jump but for the 110° squat-jump the correlation was trivial ($r = 0.06$). The starting knee angle we used was 110° owing to its reported specificity to the knee angles encountered in the

short sprints (Young et al., 2001). Perhaps the influence of starting knee angle is critical to the relationship between concentric-only machine squat-jump strength measures and short sprint ability. Any future study into such relationships should compare at least two different starting knee angles. It may be that the length-tension relationship of the hip and knee extensors at lower starting knee angles is biomechanically less specific to the actual knee angles encountered in 10-m sprints. Furthermore, using an acyclic, bilateral, vertical assessment to predict cyclic, unilateral sprint performance that involves both vertical and horizontal force production is problematic in terms of face validity. Indeed, biomechanical similarity of assessment and training equipment to the functional performance task is a fundamental tenet of specificity (Sale and MacDougall, 1981; Young, McDowell, and Scarlett, 2001). Developing assessment procedures with improved logical validity should therefore be a focus of further research.

Conclusions

The purposes of this study were to examine the inter-relationships between maximal strength, traditional, explosive and Zatsiorsky's measures of force and power measures at different loads, and how they related to 10-m sprinting ability in well-trained sportsmen. The low correlations between strength and power measures provide some evidence that the common practice of focussing on maximising strength with the intention of improving power output may be misguided. Strength, force, and power variables also appear to be less related at heavier loads. Further analysis of the force-time and power-time curves of dynamic lifts at different loads for time to peaks and inter-correlation of strength variables would be worthwhile. Our results also cast doubt on the efficacy of increasing explosive force and power in a machine squat-jump with the intention of improving sprint ability in well-trained athletes. Developing assessment procedures with improved logical validity should therefore be a focus of further research. A study tracking change in each of the force and power measures, and how they are associated with change in sprint performance would offer greater insight into best training practice.

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CHAPTER 6. SQUAT-JUMP TRAINING AT MAXIMAL POWER LOADS VERSUS HEAVY LOADS: EFFECT ON SPRINT ABILITY

Prelude

Hitherto, this thesis has described machine squat-jump kinetic and kinematic measures and their relationship to sprint performance. Although previous chapters established that Pmax was not usefully related to sprint performance, it was acknowledged that correlations do not imply cause and effect. Thus, a training study examining the relationships between change in strength and power measures and change in sprint performance was required to quantify optimal training prescription. Training at a load maximising power output (Pmax) is an intuitively appealing strategy for enhancement of performance that has received little research attention despite considerable interest in Pmax testing and monitoring by practitioners. No study to date has specifically identified peak power outputs for each individual on the specific isoinertial resistance training exercise used in both testing and training, tracked strength and power outputs on that exercise and related these changes to change in sprint ability over a training period. Accordingly, this chapter compared training at individual Pmax on the machine squat-jump versus training at heavy loads on sprint performance. Also examined were a multitude of other kinetic and kinematic measures with the intention of elucidating any superior measure associated with sprint performance enhancement.

Introduction

The optimal combination of training variables for the improvement of functional performance such as sprinting, jumping, and throwing remains an area of great contention amongst sports science researchers and strength and conditioning practitioners. A key area of conjecture is which training load, usually expressed as a percent of one repetition maximum (%1RM) and associated training velocity should be used. Some researchers proclaim the superiority of heavy (80 %1RM and above) loading schemes (Schmidtbleicher and Haralambie, 1981; Tricoli et al., 2005; Young and Bilby 1993), some lighter (50-60 %1RM and below) (Lyttle et al., 1996; McBride et al., 2002; Wilson et al., 1993) and some a combination of loads (Adams et al., 1992; Harris et al., 2000). Other studies have reported no statistical difference in training effects between groups utilizing different loads (Blazevich and Jenkins, 1997; Cronin, McNair, and Marshall, 2001c).

A number of researchers and practitioners have postulated that training at loads where mechanical power output is maximised (Pmax) is optimal for improvements in functional performance (Baker et al., 1999a; Kaneko et al., 1983; Newton et al., 1994; Sleivert et al., 2004; Stone, 1993; Wilson et al., 1993; Zink et al., 2006). Progressing this contention, some studies have sought to determine the relative effectiveness of training with so-called Pmax loads versus other training loads (Blazevich et al., 2002; Harris et al., 2000). Blazevich and Jenkins (2002) hypothesised that training with loads corresponding to optimum power output should result in superior improvements in 20-m sprint times over the course of a seven week training period in nationally ranked sprinters. One group trained with 30-50 %1RM, and the other 70-90 %1RM. Both groups significantly decreased sprint times (-4.3% and -2.9% for the 70-90 %1RM and 30-50 %1RM groups respectively) but there were no significant differences between groups. Harris et al. (2000) also examined the effects of training at either high force (80 %1RM), high power (30-45 %1RM), or a combination of loads using various lower body exercises on strength, power and 30-m sprint time over a 9-week training period. Only the combination training group significantly improved sprint times (-1.6%). Results from these two studies are difficult to interpret however, as total training volume (for example, sets x reps x load) was not equated between groups, so the reported differences between the training protocols could be a result of differences in

training volume rather than specific kinematic and kinetic characteristics of the different loading intensities (Harris, Cronin, and Keogh, 2007). Additionally, both studies chose the so-called high power loads based on previous research which reported that power was maximised at approximately 30% of maximum isometric strength (Kaneko et al., 1983; Wilson et al., 1993). Neither study identified Pmax for each individual, or for the respective resistance training exercise used for testing and training.

A common assumption of many authors is that power is maximised at loads of 30 to 45 %1RM, (Baker, 2001a; Bemben et al., 1991; Kaneko et al., 1983; Mayhew et al., 1992; Wilson et al., 1993). However, there are large inter-individual, and exercise specific differences in the load where Pmax occurs (Harris, Cronin, and Hopkins, 2007b; Sleivert et al., 2004). Hence, it would seem important to specifically identify the load where Pmax occurs for each individual subject on specific exercises to adequately investigate the effects of Pmax training on force, power and functional performance. Only two studies to date have attempted this (Newton et al., 2006; Wilson et al., 1993), but each is characterised by its own methodological limitations. Newton et al. (2006) reported that four weeks of Smith-machine jump-squat training at the load where mechanical power was maximised for each individual attenuated declining jump performance in women volleyball athletes during a competitive season. Average power (12.0%) and force (12.4%) during a loaded Smith-machine jump-squat were also significantly improved post-training, in addition to significant increases for peak force (5.7%) and peak velocity (8.8%) during an unloaded jump-squat. No control group or alternative training groups were investigated owing to the ethical issue of using elite competitive athletes in-season as subjects, so no comparison could be made to other training modalities, thus limiting the validity of determining the superiority of such training. Additionally, although it was specifically noted that training loads were continually adjusted to the point where maximal mechanical power was maximised for each individual, the methods used for determining peak power were not clear, and the loads used during training were not reported as %1RM thus applying the recommendations to a practical setting is problematic.

Wilson et al. (1993) also investigated the effect of training with individual Pmax loads over a 10-week period. One group trained with maximal power loads but, in contrast to the study by Newton et al. (2006), Pmax was identified as the load which maximised

mean mechanical power output rather than peak mechanical power output. It was stated that loads were around 30% of maximum isometric force. Two other groups trained with either heavy loads (6-10 RM ~75 – 84 %1RM), or with body-weight jumps. Pre- and post-testing included 30-m sprint times and jump height. The Pmax training resulted in an improvement in sprint times (-1.5%) described as 'approaching statistically significant' whereas sprint times for the other two training groups were virtually un-changed (-0.2%). The Pmax group also experienced significantly greater gains in jump height (17.6%) than the other groups (5.1% and 10.3% for the heavy load and body weight groups respectively) pre- to post-training. The authors concluded that their results strongly suggest the superiority of training at Pmax loads for the improvement of athletic performance and stated that loads of 30% of maximum should be used. However, the study suffers from a similar methodological problem to that of Newton et al. (2006) in that the methods for determining Pmax are not clearly described. Also, volume was not equated between training groups.

No study to date has specifically identified peak power outputs for each individual on the specific isoinertial resistance training exercise used in both testing and training. Furthermore, no study has tracked strength, force, and power outputs on that exercise and related these changes to change in sprint ability over a training period. Thus, this study aimed to quantify the effect of training at individual peak Pmax load versus training at heavy loads (80 %1RM) on changes in concentric strength and power outputs, and sprint ability in well-trained athletes after 7-weeks of equi-volume training on a machine squat-jump.

Methods

Approach to the problem

To determine the effectiveness of training at Pmax on change in sprint times in well-trained athletes, two groups trained for seven weeks with a machine squat-jump at either 80 %1RM or at the load where peak power was maximised for the individual. Within-subject modelling was used to estimate the change in force and power outputs at 55% of pre-training 1RM. The relationship between these variables was determined with

106

correlational analysis. Percent changes were standardised to make magnitude based inferences on the difference between groups.

Subjects

Eighteen elite-level rugby-league players from one first-grade squad volunteered and provided written consent for testing as part of their contractual arrangements with their squad. Their age, mass and height were 21.8 ± 4.0 y, 96.2 ± 9.9 kg, and 180.7 ± 4.6 cm (mean $\pm$ SD). All had experience of resistance training (3.6 ± 2.2 y). The AUT University institutional ethics committee approved all procedures.

Equipment

Subjects performed their assessments on a customised standing hack-squat machine (Fitness Works, Auckland, NZ) described previously (Harris et al., 2007a). A linear position transducer (P-80A, Unimeasure, Oregon – mean sensitivity 0.499 mV/V/mm, linearity 0.05 % full scale) was attached to the sled and measured vertical displacement of the sled with an accuracy of 0.01 cm. Data was sampled at 500 Hz and collected via a computer based data acquisition and analysis program (Labview^{TM} 6.1. National Instruments, Austin, Texas). The measurement of force as described in this experiment has been verified by comparison of the linear transducer data with data gathered simultaneously from an accelerometer and a force platform across movement types (concentric only and rebound bench presses - squat, countermovement and drop jumps), loads (40 - 80 %1RM) and sampling frequencies (200 - 1000 Hz). The data from the linear transducer was shown to be reliable (coefficient of variation 2.1 - 8.4%, and intraclass correlation coefficient = 0.92 - 0.98 for measures of mean and peak force) and valid across these conditions (Cronin et al., 2004). The validity of utilising exclusively a linear position transducer to determine power outputs in squat-jumps has also been reported previously (Hori et al., 2006).

Sprint times over 10- and 30-m were measured using the Kinematic Measurement System (KMS, Optimal Kinetics, IN). The within-trial variability (coefficient of variation $\le$ 1.2%) of this procedure has been reported previously (Cronin and Hansen, 2005).

Procedures

The maximal strength (1RM) and concentric power-load spectrum (20 - 80 %1RM) were assessed for each subject on three occasions. The first occasion was prior to a 4-week familiarisation period. The second occasion was immediately prior to a 7-week training period, and the final occasion was immediately post the 7-week training period. Instructions were issued to subjects to standardise pre-test preparation (exercise levels, nutrition, etc.) as much as possible in the 24-hour period preceding the testing session. At each session the subjects first performed a standardised warm-up procedure consisting of running, dynamic stretching and ball drills.

At the first testing occasion, subjects were first familiarised with the machine hack-squat by performing two warm-up sets at a light load (40-60 kg). In an effort to be specific to the knee angles encountered in sprinting (Young et al. 2001), start position was standardised to 110º at the knee using a goniometer (centred at the lateral epicondyle of the knee and aligned to the lateral malleolus and greater trochanter). Adjustable mechanical brakes were used to fix the stop-start position for the machine at the 110º knee angle. Foot position was self selected by subjects but standardised to within five centimetres between all subjects. Two to three trials were then performed to establish 1RM. After a standardised rest period, a load of 20% of the individual's 1RM was placed on the squat machine and the subjects completed one lift with maximal effort. A 1-minute rest period was then allowed before the load was increased to 30% of the individual's 1RM. This process was repeated for loads 40, 50, 60, 70, and 80%, of the individual's 1RM. Subjects were given instructions to move every load with maximal effort and jump if the load permitted. All lifts were commenced from the standardised starting position thus the movement was concentric only.

During the second session, all subjects sprint times were first assessed over 10- and 30-m. The starting position was standardised as a two point crouched position with the left toe 30 cm back from the starting line and the right toe approximately in line with the heel of the left foot. All assessments were performed on an indoor court surface and subjects wore rubber-soled track shoes. The average of the two best trials was used for subsequent analysis. After a rest period of ten minutes, strength was measured as per the protocol outlined for testing occasion one, thus 1RM and the associated training loads were re-assessed immediately prior to the start of the training period. Sprint

times, strength and kinetic/kinematic outputs across 20-80 %1RM were assessed again at the third testing occasion.

Training

Prior to the training period commencing, a 4-week familiarisation period was first prescribed for both groups to negate any learning effects and increase the reliability of baseline measures. Training for this period consisted of three sets of eight repetitions at 30 %1RM and three sets of five repetitions at 80 %1RM on the machine hack-squat for all subjects, in addition to regular strength training and squad sessions. Training took place during the pre-season specific preparation phase of the annual periodised plan for the elite training squad, thus all subjects were considered to be approaching peak condition. All sessions were monitored by strength and conditioning trainers.

Immediately post the second assessment occasion, subjects were randomly allocated into two separate training groups (n = 9 per-group) based on approximate matching of sprint times, 1RM and body mass. Pre-training strength, speed and body mass values can be observed in Table 6.1. No clear differences were observed between groups on any of the variables of interest. Training was performed in two micro-cycles of 3-weeks separated by a 1-week unload cycle. Each group completed six training sessions in the first three weeks, one training session in week four (unload week), and six further sessions in weeks five to seven inclusive. Rather than changing the program variables in the second 3-week micro-cycle, subjects were encouraged to attempt to increase the explosiveness of their movement. One group performed machine squat-jumps at 80 %1RM (Gr80), and one at the load where individual peak power output was maximised (GrPmax), as identified by the testing outlined above. Peak power occurred at 23.3 ±5.2 and 26.3 ±7.4 %1RM for Gr80 and GrPmax respectively. Total training volume was equated between groups by multiplying sets x reps x load. Gr80 performed five sets of five repetitions with a 2-minute rest between sets, and GrPmax performed six sets of ten-twelve repetitions with a 2-minute rest between sets. Subjects were instructed and encouraged to perform all training regardless of load as explosively as possible and jump if the load permitted. Owing to injuries unrelated to the study, three subjects did not complete the training and testing required to qualify for inclusion in final data analysis, thus final subject numbers were 7 and 8 for Gr80 and GrPmax respectively.

In addition to the machine squat-jump training both groups performed sprint drills, other lower body exercises at various loads and upper body training twice per week. Training on the machine hack-squat therefore constituted approximately 20% of total lower-body training for either group. All training other than the machine squat-jump training was identical between groups.

Data analysis

The hack-squat displacement data were filtered using a low pass, fourth order, Butterworth filter with a cut-off frequency of 10 Hz. This filtered displacement time data was then differentiated to determine velocity and acceleration. From this data the following kinetic and kinematic variables were calculated from the start of the upward movement to the peak concentric displacement: Peak velocity; peak force; peak power; and total impulse. System mass (mass of the sled weight plus body mass of the subject) was used for all force calculations. All force and power variables were expressed as absolute values and relative to body-mass.

Statistics

Means and standard deviations are used throughout as measures of centrality and spread of data. Within-subject modelling was used to estimate the change in kinetic and kinematic outputs from pre- to post-training. To determine individual Pmax a quadratic was fitted to each subject's kinetic/kinematic output and load (in %1RM); a technique previously detailed (Harris et al., 2007a). The load chosen for final analysis was 55% of pre-training 1RM. A load of 55 %1RM was considered an appropriate compromise between the loads utilised for each group's respective training program. Thus, contraction force specificity and familiarization were accounted for. Additionally, analysis based on the pre-training load of 55 %1RM negated any effect of increased 1RM load on kinetic and kinematic outputs.

Pearson correlation coefficients were used to determine the relationship between percent change in kinetic/kinematic variables and percent change in sprint times, the magnitude of which were interpreted using Cohen's scale (Cohen, 1988): <0.10, trivial; 0.10-0.29, small; 0.30-0.49, moderate; ≥0.50, large. Correlations were applied to each group

separately, and averaged to provide an overall analysis. Change in strength and speed are expressed as percent change and effect sizes (pre-test minus post-test divided by the standard deviation of the pre-test). The difference between groups (±90% confidence limits) is expressed with a qualitative inference of the magnitude of the difference (Cohen, 1988). Inferences about the true (large-sample) value of the correlations and percent differences were based on uncertainty in their magnitude (Batterham et al., 2006); if the 90% confidence interval (derived for correlations via the Fisher z transformation) (Fisher, 1921) overlapped small positive and negative values, the magnitude was deemed unclear; otherwise the magnitude was deemed to be the observed magnitude. For trivial-small correlations the confidence limits were ~±0.55. Thus the power of this study was such that only correlations greater than >0.45 or <-0.45 were considered clear.

Results

The pre- and post-training values for sprint times, strength and body mass of both groups can be observed in Table 6.1. Percent change in strength and sprint times pre- to post-training for both groups with percent difference (± confidence limits CL) and a qualitative inference of the magnitude of the difference are detailed in Table 6.2. The confidence limits for the change scores within each group are not detailed in the table, but from first principles confidence limits are ~±0.7 of the standard deviation of the change scores. Both groups decreased sprint times over 10- and 30-m distances, and both groups increased 1RM and 1RM/kg body mass. Only the percent change in 1RM/kg body mass, and percent change in body mass pre- to post-training were considered clearly different between groups. The 1RM strength of Gr80 increased to greater effect whereas the Pmax training resulted in a relatively greater increase in body mass.

Table 6.1. Pre- and post 7-week training values for strength and speed for each group

	80 %1RM group		P_{max} group	
	Pre-training	Post-training	Pre-training	Post-training
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
10-m sprint time (s)	1.83 ± 0.05	1.78 ± 0.05	1.86 ± 0.07	1.83 ± 0.06
30-m sprint time (s)	4.18 ± 0.12	4.11 ± 0.12	4.22 ± 0.18	4.17 ± 0.14
1RM (kg)	302 ± 45	352 ± 43	326 ± 52	356 ± 54
1RM / kg body mass (kg/mass)	3.21 ± 0.37	3.74 ± 0.39	3.36 ± 0.58	3.64 ± 0.59
Body mass (kg)	94 ± 10	94 ± 10	98 ± 9	99 ± 8

Table 6.2. Percent change in strength and sprint times for the 80 %1RM and Pmax groups with percent difference (±90% confidence limits CL), effect sizes (pre-test minus post-test divided by the standard deviation of the pre-test), and qualitative inference on the magnitude of the difference.

	80 %1RM group		P_{max} group		Difference (P_{max} group - 80 %1RM group)	
	Mean ± SD	Effect size	Mean ± SD	Effect size	Mean, ±90% CL	Qualitative inference
10-m sprint time	-2.9 ± -3.2	0.88	-1.3 ± -2.2	0.68	1.7, ±3.0	unclear
30-m sprint time	-1.9 ± -2.8	0.74	-1.2 ± -2.0	0.63	0.7, ±2.4	unclear
1RM	15.0 ± 9.0	0.56	10.5 ± 7.9	0.45	-3.9, ±8.7	unclear
1RM / kg body mass	15.3 ± 9.1	0.63	9.0 ± 7.9	0.47	-5.5, ±8.4	Trivial to moderate
Body mass	0.2 ± 1.1	0.11	1.1 ± 1.2	0.13	0.8, ±1.1	Trivial

Pre-training, peak power was maximised at 23.3 ±5.2 and 26.3 ±7.4 %1RM for Gr80 and Pmax respectively. The range of loads where Pmax occurred for all subjects was 20.0 - 43.5 %1RM. Post-training there was no clear change in these values for either group.

The percent change pre- to post-training for the kinetic/kinematic outputs of each group at 55 % pre-training 1RM, difference between groups and qualitative inference of the magnitude of the difference are shown in Table 6.3. All of the kinetic/kinematic variables assessed decreased pre- to post-training. Generally, the GrPmax outputs decreased to a less extent than Gr80 (except for impulse) but only the percent change in peak power, peak power/kg body mass, and peak velocity were considered to be clearly different between groups. That is, the decrease in these variables was clearly less in GrPmax as compared to Gr80.

Table 6.3. Percent change in kinetic/kinematic outputs at 55 % pre-training1RM and percent differences (±90% confidence limits CL) between groups from pre- to post 7-week training period with a qualitative inference on the magnitude of the difference.

	80 %1RM group	P_{max} group	Difference (P_{max} group - 80 %1RM group)	
	Mean ± SD	Mean ± SD	Mean, ±90% CL	Qualitative inference
Peak velocity	-7.5 ± 6.4	-2.4 ± 9.7	9.7, ±7.6	Trivial to moderate beneficial
Peak force	-8.8 ± 9.9	-2.2 ± 10.1	10.1, ±11.7	unclear
Peak force / kg body mass	-9.9 ± 8.8	-4.5 ± 10.1	6.0, ±9.7	unclear
Peak power	-17.1 ± 9.1	-6.0 ± 18.3	18.3, ±15.3	Trivial to large beneficial
Peak power / kg body mass	-17.1 ± 9.0	-6.5 ± 16.6	16.6, ±13.5	Trivial to very-large beneficial
Impulse	-7.3 ± 14.2	-11.2 ± 15.5	15.5, ±14.0	unclear
Impulse / kg body mass	-7.9 ± 14.5	-11.7 ± 16.2	16.2, ±14.3	unclear

Values for the correlation coefficients between percent change in kinetic/kinematic outputs and percent change in sprint times were all positive and of trivial to moderate magnitude (r = 0.11 to 0.43, and r = 0.16 to 0.50 for 10- and 30-m sprint times respectively). Correlational values between percent change in 1RM and percent change in sprint times were of negative moderate magnitude (r = -0.28 and r = -0.34 for 10- and 30-m sprint times respectively). Similar values were observed for the correlation between percent change in 1RM/kg body mass and sprint times (r = -0.29 and r = -0.33 for 10- and 30-m sprint times respectively).

Discussion

The subjects in the present study were a well-trained sample and as fast and strong as other similar athletes (Baker, 1999; Cronin and Hansen, 2005). Of interest therefore, was establishing whether training at individually determined Pmax load provided for superior functional performance improvements compared to heavy load training.

A key finding was that, although the greatest decrease in sprint times were observed in Gr80 (-2.9 ±3.2 and -1.9 ±2.8% for 10- and 30-m sprint times respectively), there were no clear differences between groups. Additionally, change in neither group was considered to be 'clear' based on 90% confidence limits. It should be noted however, that improvements in sprint times for well-trained athletes of as little as 1% may have physiological, but not statistical significance and may be the difference in terms of

performance (Hopkins, 2005). The improvements we observed in sprint times (-1.8 ±2.5% ES -0.49, average of both distances and both groups) are similar to the few other studies that have tracked changes in sprint times in well-trained athletes over a training period (Blazevich et al., 2002; Harris et al., 2000; McBride et al., 2002), although there are some contrasts in terms of the relative efficacy of heavy or so-called lighter load training. For example, McBride et al. (2002) investigated the effect of eight weeks of equi-volume training using either heavy (80 %1RM) or light (30 %1RM) load jump-squats on the development of sprint ability, strength and power outputs. In contrast to our results, significantly greater improvements in 10-m sprint times (-1.6%) were reported post-training for the 30 %1RM training group compared to the 80 %1RM training group. Jump-squat peak velocity (at 30 %1RM) was also significantly improved (8.1%), but no differences were observed between groups for change in sprint times over 5- and 20-m, nor for the other strength and power outputs assessed. McBride et al. (2002) concluded that the lighter load training resulted in increased movement velocity capabilities compared to the heavier load training. Given the conflicting results between our study and that of Mc Bride et al. (2002), it may be that the key strength stimulus for the development of sprint ability is the maximum voluntary effort or intent to develop force as fast as possible and not the size of the load and concomitant limb velocity (Behm and Sale, 1993). If the rate of muscular tension development and motor unit activation in a maximum effort is relatively constant for an individual independent of the external movement velocity and external load (Sale et al., 1981), the absence of a load specific effect would appear hypothetically logical.

Tracking percent change in peak power and impulse were of specific interest given they are perceived as theoretically important determinants of sprinting ability (Hay, 1992). However, neither percent change in power nor impulse were clearly, or negatively correlated to percent change in sprint times ($r = 0.25$ to 0.44). The only negative correlations observed between percent change in any strength or kinetic/kinematic output and percent change in sprint times were for maximal strength, as assessed by 1RM and 1RM/kg body mass. It might be anticipated that kinetic/kinematic outputs expressed relative to body mass would be more clearly related to sprint ability (Baker et al., 1999a), but this was not the case; correlations were also positive and generally of unclear magnitude. Given these findings, the value of instrumenting a machine hack-

squat for kinetic/kinematic outputs appears limited and perhaps simply increasing maximal strength is of greater influence on sprinting ability.

Gr80 experienced greater increases in strength (1RM and 1RM/kg body mass) than GrPmax, although only the difference between groups for percent change in 1RM/kg body mass was considered to be clear (-6.0 ±8.2%). It is not unexpected that the group training with heavier loads should experience greater improvements in strength relative to body mass (Kraemer, Duncan, and Volek, 1998). Additionally, GrPmax increased body mass more than Gr80, although changes were trivial (ES 0.03 – 0.11) for either group. Despite equating for overall volume between groups, it is possible that the greater mechanical overload experienced by GrPmax (i.e. greater total work, force, time under tension) would explain this difference (Enoka, 1997). GrPmax also experienced an increase in 1RM strength (15.0 ±9.0% ES = 0.50), results that are similar to other studies that have observed strength increases in training groups utilizing training loads from opposing ends of the load spectrum. For example, McBride et al. (2002) observed significant increases in 1RM squat strength for both heavy and light training groups (8.3 and 10.5% respectively) with no significant differences between groups. A further consideration in the present study is that both groups performed additional lower body training at a variety of loads (30 - 90 %1RM), so some transfer of training effect was expected between strength gained from the other training performed and strength gained in the machine hack-squat.

In terms of the relationship between change in strength and change in sprint times, our results support the findings of Cronin et al. (2007) who reviewed training studies that assessed strength effects on sprint times and concluded that, for highly trained athletes moderate to large (ES = 0.71 to 1.2) squat strength changes (~12%) may be needed for moderate (ES = 0.74 to 0.94) changes (> -2.0%) in sprint time. The decrease in sprint times for both groups (~ -1.83%, ES ~ -0.49), and increased machine hack-squat 1RM (12.7 ±8.5%, ES ~ 0.70), are similar to the ratio proposed by Cronin et al. (2007). However, a surprising finding is that despite maximal strength increases, all of the kinetic/kinematic outputs decreased over the training period, a result difficult to explain. It may be postulated that 'biological noise', in terms of fatigue and/or a decreased effort in the post-training testing occasion, was at least partially responsible for the decreases. Given the strength and speed improvements observed at the post-training tests it seems

unlikely that biological noise was a contributing factor. Perhaps the subjects experienced a plateau in power owing to a relatively long cycle of training without change in stimuli, or because they had achieved optimal adaptation in the early pre-training familiarisation phase. Certainly it would seem advanced athletes are more challenging to condition that their less experienced counterparts and may require more frequent periodisation of program variables (Harris et al. 2007a).

Practical applications

The reader needs to be cognizant of the limitations of this study when interpreting the results, some of which have been outlined previously (Harris et al., 2007a). Briefly, these are: The resistance exercise (machine hack-squat) utilised a purely bi-lateral, a-cyclical, vertical expression of force, and the kinetic/kinematic variables were assessed over the concentric phase of the movement possibly reducing face validity to sprinting ability. Nonetheless, given the propensity of practitioners to use squats and derivatives in training, investigation of such an exercise would appear worthwhile. There are further limitations for consideration within this study. First, statistical power was compromised owing to the relatively low number of subjects. It should be noted that the subject group used in this study was the entire available group from the target population, that is, the top training squad of an elite rugby-league team. Increasing subject numbers by including subjects other than the elite training squad with the intention of providing greater statistical power would have compromised the validity of the study in terms of extrapolating findings to other similar athletes. Also because of the ethical issues in relation to using professional athletes as subjects, no non-training control group was allocated. In spite of this, we were able to compare one training modality versus the other, with all other training exactly the same between groups. Second, the total volume of the training intervention performed by either group constituted a relatively low portion (approximately 20%) of total lower body training performed by the subjects over the training period. It is entirely conceivable that the other training exercises and drills performed by each group were partly responsible for any observed changes in strength, kinetic/kinematic outputs, and speed, but to gain access to a group of professional athletes and perform experimentation we were ethically obliged to minimise disruption to normal prescribed training. Also, to allow a mechanical analysis it was important to control for as many variables as possible, thus

the study design defined specific but limited differences in training interventions between groups. Finally, tracking percent change in strength and power outputs to percent change in sprint times and performing a correlational analysis is attenuated by error of measurement yet such an approach surely provides greater insight into which variables are related to sprint ability and subsequently which are worth developing in programs.

It is impossible to disentangle the aforementioned limitations of this study from the practical applications. However, it appears that training at the load that maximises individual peak power output for this particular exercise with a sample of professional team-sport athletes was no more effective for improving sprint ability than training at heavy loads and the changes in power output were not usefully related to changes in sprint ability. The preoccupation of training with loads that maximise power output in machine squat-jumps with the intention of improving sprint ability may be misplaced. Biomechanical specificity to the functional task would seem a fundamental tenet of training adaptations. A detailed investigation of the adaptive associations between strength and power outputs in other commonly prescribed exercises and sprint performance would be most useful.

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This PhD sought to address several areas of contention in strength and conditioning research and practice arising mostly as a consequence of methodological discrepancies. Specifically, a more detailed understanding of the kinetic and kinematic outputs associated with a squat-jump, and their inter-relationships and effects on sprint ability.

A review of the literature revealed several key methodological areas to be considered in the design of the experimental studies within this thesis. First, isoinertial dynamometry clearly provides greater face validity for the assessment and development of strength and power for the functional performance movements implicit in most sports. Irrespective of the type of dynamometry used, strength and power gains are quite specific to the testing mode, so it is important that testing mode is closely matched to training and the athletic task of interest. Second, if the intention of research is contributing to the enhancement of sporting performance of top-level athletes then the choice of study subjects is critical. The validity of generalising findings from subjects with little or no training experience (novices) or non-athletes to well-trained athletes is extremely problematic. There is strong evidence that novices respond with generic strength increases to training programmes, and that non-athletes differ in strength and power characteristics to their athletic counterparts. Although novice subjects and/or student populations are generally accessible and can be easily divided into experimental and control groups, it is more difficult to gain access to a cohort of subjects from an athletic population, and particularly have one group act as a control. Third, most studies have reported only the load used during training and/or testing and not the mechanical stimuli associated with the use of these loads. It should be remembered that these mechanical stimuli (i.e. total session work, time under tension, etc.) determine hormonal and metabolic responses and subsequent neuromuscular adaptation. Therefore understanding the effect of load and exercise type is imperative for the advancement of strength and conditioning practice. For example, so-called ballistic movements produce distinct kinetic and kinematic characteristics compared to movements where a load is not projected, so exercises and instructions issued to subjects must be clearly described. Fourth, the methods of collection and calculation of power measures influence final outputs. For resistance training techniques using fixed plane of motion such as machine squats, it would appear that differentiation of data from a single position transducer is

satisfactory. The use of a force-plate in conjunction with a position transducer is desirable but not as accessible due to cost and portability and therefore not as transferable to most practical settings. In terms of calculating force outputs, body mass should be added to the load mass for so-called ballistic lower body movements such as squat-jumps. Excluding body mass alters the force and power output characteristics across the load spectrum. Finally, in training studies the equating of total training volume is necessary in order to distinguish effects of training interventions over effects associated simply with differences in total training volume.

Squat-jumps are very commonly used in research and training practice but studies investigating the kinetic and kinematic outputs of squat-jumps across a full load spectrum (as a percentage of 1RM strength) are very limited and contradictory. In particular, the reported point on the load spectrum where mechanical power output is maximised (Pmax) varies from 0 %1RM to 60 %1RM. Additionally, the difference in power outputs each side of Pmax has not been comprehensively quantified. Study one sought to describe the kinetic and kinematic outputs associated with a machine squat-jump across 10-100 %1RM in well-trained athletes, with an emphasis on power. Peak and mean power occurred at 21.6 ± 7.1 %1RM and 39.0 ± 8.6 %1RM respectively although there was considerable individual variation in these maxima. A broad plateau in power outputs was evident for most subjects with at most a 9.9% (90% confidence limits ±2.4%) difference in peak or mean power at loads up to 20 %1RM either side of Pmax.

Maximising 1RM strength seems to be entrenched in conditioning practice based on the assumption that it is an underpinning quality of explosive muscular performance. Quantification of the relationship between strength and power measures has been reported by a number of studies, but comparisons and definitive conclusions remain elusive. In addition to the aforementioned methodological issues, the interpretations and representations of explosive power measures are often ambiguous. Accordingly, study two investigated the interrelationships between machine squat-jump strength and a range of power measures at different loads. The magnitude of the correlations between maximal strength and power measures were generally low or moderate. Strength, force, and power variables were also less related at heavier loads, providing

some indication that there is a divergence in the characteristics of the force-time and power-time curves as load increases.

Given the apparent popularity of the squat-jump as a mainstay exercise in many gym-based programmes seeking to improve functional performance, the next area of conjecture that this thesis sought to address was the relationship of squat-jump strength and kinetic / kinematic outputs with functional performance. The functional performance measure of particular interest was sprint performance over short distances because they are so widespread and important in sport. The most common approach to quantifying such a relationship is correlational analysis. It is important to acknowledge that correlations do not imply cause and effect, but establishing relationships does provide an insight into which gym-based strength outputs may be of prognostic and diagnostic value to sprint performance. The initial review chapter established that the magnitude of the correlations between strength and power variables and sprint performance differed markedly within the research, although there was some indication that strength and peak power relative to body mass are related to sprint ability. Hence, the second and third studies of this thesis investigated the relationship between a multitude of kinetic and kinematic measures of a machine squat-jump and short sprint ability in well-trained athletes. Included in the investigation were a number of explosive power measures, as it was thought they may be more related to sprint ability than some of the more traditional measures of strength and power. Only 1RM strength, work and total impulse (all relative to body mass) provided any indication of outputs related to sprint performance, albeit with only moderate correlations ($r = \sim$ -0.3). Practically no relationship between any explosive power measure and sprint performance was found. A training study investigating change in performance measures was needed to provide more robust insight.

The final study of this thesis was a training intervention. Research and practitioners have been preoccupied with the hypothetical transference of training at peak power output to functional performance. Despite this, no study to date has specifically identified peak power outputs for each individual on the specific isoinertial resistance training exercise used in both testing and training, tracked a range of kinetic and kinematic measures on that exercise and related these changes to change in sprint ability. Thus, chapter six aimed to quantify the effect of training at individual peak

Pmax load versus training at heavy loads (80 %1RM) on changes in strength and power outputs, and sprint ability. No clear differences were observed between groups for change in sprint times, so it appears that training at the load that maximises individual peak power output for this particular exercise with a sample of professional team-sport athletes was no more effective for improving sprint ability than training at heavy loads. Of multiple strength and power measures, only increase in maximal strength (absolute and relative to body mass) was somewhat usefully related to improvement in sprint ability albeit at low to moderate magnitude (r = -0.28 to -0.34). The changes in power outputs were not usefully related to changes in sprint ability.

(De)limitations

It is important to be cognizant of the following limitations when interpreting the results of this thesis:

- The exclusive functional performance measure investigated in this thesis was sprint performance. Findings may not be applicable to other common measures of performance such as jump ability.
- Findings from this study are specific to the standing machine squat-jump only, hence may not translate to other common squat derivative exercises, such as the free-weight squat-jump.
- Only single repetitions were performed at each load. Typically, training involves multiple repeated repetitions; kinetic and kinematic outputs may differ between multiple and single repetitions.
- In the training study (chapter six) statistical power was compromised owing to the relatively low number of subjects. It should be noted that the subject group used in this study was the entire available group from the target population; that is, the top training squad of an elite rugby-league team. Increasing subject numbers by including subjects other than the elite training squad with the intention of providing greater statistical power would have compromised the validity of the study in terms of extrapolating findings to other similar athletes. In addition, because of the ethical issues in relation to using professional athletes as subjects, no non-training control group was allocated.

- The total volume of the training intervention performed by either group constituted a relatively low portion (approximately 20%) of total lower body training performed by the subjects over the training period. It is entirely conceivable that the other training exercises and drills performed by each group were partly responsible for any observed changes in strength, kinetic/kinematic outputs, and speed.

Future research

This thesis has addressed several areas of conjecture and contention in the research on strength and power training for functional performance. In the process, several areas requiring further clarification have arisen:

- Methodological designs must be closely considered. Future studies should concentrate on using experienced subjects, preferably from an athletic population. Ideally these training studies should use specific isoinertial loading schemes and the testing protocols should assess performance over the force-velocity continuum so as to gain a greater understanding of the effect of load on muscular function. When comparing the effectiveness of multiple training strategies the volume of training should be equated between subject groups to allow direct comparison between the training methods. Further analyses of kinetic and kinematic variables will provide greater insight into the stimuli required for strength and power development than simply measuring the changes in strength.

- A detailed investigation of the adaptive associations between strength and power outputs in other commonly prescribed gym-based exercises and sprint performance would quantify hypothetical usefulness, provided that methodological issues are addressed.

- Developing assessment procedures with improved logical validity to the functional performance task should be prioritised. For sprinting, gym-based exercises using more movement and contraction type specificity should be investigated. For example, the kinetic and kinematic measures associated with sled towing at different loads and their relationships to sprint ability.

- Emphasis should be placed on tracking the relationships between change in kinetic / kinematic measures and change in sprint performance over a training period. Additionally, comparison between training groups or to a control group would provide an opportunity to quantify the relative efficacy of one training scheme over another.
- The kinetic and kinematic outputs across a set need further investigation.
- Further analysis of the force-time and power-time curves of dynamic lifts at different loads for time to peaks and inter-correlation of strength variables is needed.

Conclusions and practical applications

Given the inter-individual differences and insubstantial changes in power output each side of Pmax, the preoccupation of research to identify one load as the training load for maximising mechanical power output would seem less important than many think. Nonetheless, practitioners need to: 1) identify the practical significance of using mean or peak Pmax; 2) ensure that Pmax is individualised due to large inter-individual differences; 3) ensure that Pmax is identified per movement as the load that maximises Pmax most likely differs for each exercise used in the gym setting; and, 4) Pmax needs constant monitoring and recalculating.

The emphasis on training with loads that maximise power output in machine squat-jumps with the intention of improving sprint ability may be misplaced. It may be that the key strength stimulus for the development of sprint ability is the maximum voluntary effort or intent to develop force as fast as possible and not the size of the load and concomitant limb velocity, so training load may therefore be of less influence than previously perceived. Nonetheless, only change in 1RM strength was found to be usefully related to change in sprint ability; given that heavy training loads are known to improve maximal strength inclusion of heavy load training would appear worthwhile. Until training studies address the limitations discussed throughout this paper the best course of action for those interested in improving sprint performance may be to use a mixed training strategy using both heavy and light loads. Realising that all human movement is an integration of force and velocity, such an approach is intuitively appealing. Also prudent may be continuously adjusting the resistances used for power

training, particularly given that a periodised approach to programming is considered most effective.

Instrumentation of the machine squat-jump with the intention of extracting power measures meaningfully related to sprint performance is patently limited by a fundamental lack of biomechanical specificity to sprint performance. The machine squat-jump utilised in this thesis involved bi-lateral, vertical expressions of force in a fixed plane of motion, versus the unilateral, mostly horizontal force expression required in sprints. Also, only concentric measures were assessed versus the stretch shortening cycle activity implicit in sprinting. Whether or not similar results would be found in studies using other common gym-based exercises such as free-weight counter-movement squats is worthy of investigation. The influence of squat depth or starting knee angle also needs more detailed analysis. More importantly, investigation of the kinetic and kinematic outputs of gym-based exercises with greater face validity to sprinting should be prioritised, for example loaded sled towing. Nevertheless, that the machine squat-jump provided little quantifiable evidence of sprint ability enhancement does not arbitrarily mean it is of little use to other functional performance measures.

Strength and power change in any one exercise probably does not accurately reflect the cumulative training effect of a total exercise programme, particularly in well-trained athletes who may experience diminished returns from training over time. Given that gym-based programmes for sporting performance typically include multiple exercises per body part, examination of performance changes across all prescribed exercises should provide greater insight into potentially useful associations between strength qualities and functional performance.

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Appendix 1. Ethics approval form

AUT

Academic Registry – Academic Services

To: John Cronin
From: **Madeline Banda**
Date: 16 August 2002
Subject: 02/72 Equi-force loading on a new dynamometer and functional performance

Dear John

Thank you for providing clarification of your ethics application as requested by AUTEC. Your application is approved for a period of two years until 16 August 2004.

You are required to submit the following to AUTEC:

- A brief annual progress report indicating compliance with the ethical approval given.
- A brief statement on the status of the project at the end of the period of approval or on completion of the project, whichever comes sooner.
- A request for renewal of approval if the project has not been completed by the end of the period of approval.

Please note that the Committee grants ethical approval only. If management approval from an institution/organisation is required, it is your responsibility to obtain this.

The Committee wishes you well with your research. Please include the application number and study title in all correspondence and telephone queries.

Yours sincerely

Madeline Banda
Executive Secretary
AUTEC

From the desk of …	Private Bag 92006, Auckland 1020, New Zealand
Madeline Banda	Tel: 64 9 917 9999 ext 8044
Academic Services	Fax: 64 9 917 9812

Consent to Participation in Research

Title of Project: Relationship of Force, Power and Velocity Profiles to Functional Performance
Project Supervisor: John Cronin
Researcher: Nigel Harris

- o   I have read and understood the information provided about this research project.
- o   I have had an opportunity to ask questions and to have them answered.
- o   I understand that the data recorded from the testing sessions will be stored on computer for analysis.
- o   I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. If I withdraw, I understand that all relevant data, or parts thereof, will be destroyed
- o   I agree to take part in this research.
- o   I have no injuries or medical conditions that may affect my ability to perform heavy weight training and sprinting, jumping and lunging.

Subject signature: ....

Subject name: ………………………………………….

Date: ………………………………………..

Contact Details:

Nigel Harris
Division of Sport & Recreation
Faculty of Health
Auckland University of Technology
Ph: 917-9999 extension 7301
E-mail nigel.harris@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on
16 August 2002. AUTEC Reference number 02/72

Appendix 3. Sample subject information sheet

AUT
AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Subject Information Sheet

Contact person:
Nigel Harris, PhD Candidate and Senior Lecturer, Auckland University of Technology
    Private Bag 92006, Auckland. Tel: (09) 9179999 x 7301
    nigel.harris@aut.ac.nz

Project Title
Relationship of Force, Power and Velocity Profiles to Functional Performance

Location
Testing will be conducted at the Millennium Institute of Sport & Health

Invitation
You are invited to take part in this study, which is being carried out by the Auckland University of Technology Division of Sport & Recreation postgraduate programme. Your participation in this study is voluntary. You are free to withdraw consent and discontinue participation at anytime without influencing any present and/or future involvement with the Auckland University of Technology.

Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have freely given your consent to participate, and that there has been no coercion or inducement to participate.

What is the purpose of the study?
The aim of this study is to examine the relationship between different training loads and functional performance.   These loads are commonly used in resistance training to improve sporting performance.

Selection of Subjects
Volunteers that meet the criteria will be included in this study.

These criteria include:
You are between the ages of 18 and 35 years.
You have at least one year of recent regular weight training experience.
You can squat at least your own bodyweight (total weight on bar) for one rep.
You do not currently have any injury or health problems that would impair your ability to complete the twelve-week training period.

What happens in the study?
Each subject will be required to participate in a total of three sessions (MON 4.00pm, WED 4.00pm, SAT 9.00am). During these sessions you will have your one repetition maximum (1RM - the maximum weight you can lift once) determined on a customised squat machine designed for safety.   You will also be tested for power on the same apparatus but using lighter loads. In a separate testing session you will be tested on sprinting speed and jumping height.   Please ensure that the 24 hr period before each test is as standard as possible. That is – avoid any weight training or strenuous exercise. This will aid greatly in the accuracy of the test.

What are the discomforts and risks?
There is possible risk of injury. This is however an equivalent risk to normal participation in physical training and competition.

What are the benefits?

You will gain detailed information on your strength and power capacity. This information may better aid you in planning future training programmes.

How is my privacy protected?
The identity of individuals will not be made available to any other source, and any information published elsewhere will have subject identities concealed.

Costs of Participating
The only cost to you the subject is approximately three hours of your time.

Subject Concerns
Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor. Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, madeline.banda@aut.ac.nz , Tel. 917 9999 ext 8044.

Approved by the Auckland University of Technology Ethics Committee on 16 August 2002
AUTEC Reference number 02/72

Appendix 4.

Abstracts of experimental chapters as published, in press or in review

Harris, N. K., Cronin, J. B., and Hopkins, W. G. (2007). Power outputs of a machine squat-jump across a spectrum of loads. *Journal of Strength and Conditioning Research, 21*(4), 1260-1264.

(Chapter 3)

The load that maximises mechanical power output (Pmax) has received considerable research attention owing to its perceived importance to training prescription. However, it may be that identifying Pmax is of little importance if the difference in power output about Pmax is insubstantial. Additionally, comparing the effect of load on power output between studies is problematic due to various methodological differences. The purpose of this study therefore was to quantify the concentric power output for a machine squat-jump across a spectrum of loads (10-100 %1RM). To estimate Pmax load and proximate loads a quadratic was fitted to the power output (Watts) and load (%1RM) of 18 well-trained rugby athletes. Pmax for peak and mean power output occurred at 21.6 ± 7.1 %1RM (mean ± SD) and 39.0 ± 8.6 %1RM respectively. A 20% change in load either side of the maximum resulted in a mean decrease of only 9.9% (90% confidence limits ±2.4%) and 5.4% (±0.9%) in peak and mean power respectively; standard deviations about these means (representing individual differences in the decrease) were 6.0% and 2.1% respectively (90% confidence limits ×÷1.34). It appears that most athletes have a broad peak in their power profile for peak or mean power. The preoccupation of identifying one load for maximising power output would seem less meaningful than many practitioners and scientists believe.

Harris, N. K., Cronin, J. B., & Hopkins, W. G. (2008). Relationship between sprint times and the strength/power outputs of a machine squat-jump. *Journal of Strength and Conditioning Research, 22*(3) 691-698.

(Chapter 4)

Strength testing is often used with team-sport athletes, but some measures of strength may have limited prognostic/diagnostic value in terms of the physical demands of the sport. The purpose of this study was to investigate relationships between sprint ability and the kinetic and kinematic outputs of a machine squat-jump. Thirty elite level rugby union and league athletes with an extensive resistance-training background performed bi-lateral concentric-only machine squat-jumps across loads of 20 to 90 %1RM, and sprints over 10 m and 30 or 40 m. The magnitudes of the relationships were interpreted using Pearson correlation coefficients, which had uncertainty (90% confidence limits) of ~±0.3. Correlations of 10 m sprint time with kinetic and kinematic variables (force, velocity, power and impulse) were generally positive and of moderate to strong magnitude (r = 0.32 to 0.53). The only negative correlations observed were for work, although the magnitude was small (r = -0.18 to -0.26). The correlations for 30 or 40 m sprint times were similar to those for 10 m times, although the correlation with work was positive and moderate (r = 0.35 to 0.40). Correlations of 10 m time with kinetic variables expressed relative to body mass were generally positive and of trivial to small magnitude (r = 0.01 to 0.29), with the exceptions of work (r = -0.31 to -0.34), and impulse (r = -0.34 to -0.39). Similar correlations were observed for 30 or 40 m times with kinetic measures expressed relative to body mass. Although correlations do not imply cause and effect, the focus onwith maximising power output in this particular resistance exercise to improve sprint ability appears problematic. Work and impulse are potentially important strength qualities to develop in the pursuit of improved sprinting performance.

Harris, N. K., Cronin, J. B., Hopkins, W. G., and Hansen, K. T. (2008). Inter-relationships between machine squat-jump strength, force, power and 10 m sprint times in trained sportsmen. *Journal of Sports Medicine and Physical Fitness, Submitted - in first review*.

(Chapter 5)

We examined the inter-relationships between maximal strength and explosive measures of force and power at different loads. Also investigated were the relationships between explosive measures and 10-m sprinting ability. Forty elite-level well-trained rugby union and league athletes performed 10-m sprints followed by bilateral concentric-only machine squat-jumps at 20 and 80 %1RM. The magnitudes of the inter-relationships between groups of force measures, power measures and sprint times were interpreted using Pearson correlation coefficients, which had uncertainty (90% confidence limits) of ~±0.25. Measures investigated included peak force, peak power, rate of force development, and some of Zatsiorsky's explosive measures, all expressed relative to body mass. The relationship between maximal strength and peak power was moderate at 20 %1RM ($r = 0.32$) but trivial at 80 %1RM ($r = -0.03$). Practically no relationship between any of the explosive measures and 10-m sprint ability was observed ($r = -0.01$ to 0.06). We conclude that the common practice of focussing on maximising strength to improve power output in well-trained sportsmen may be misguided. Our results also cast doubt on the efficacy of increasing explosive force and power in a machine squat-jump with the intention of improving sprint ability in well-trained athletes.

Harris, N. K., Cronin, J. B., Hopkins, W. G., and Hansen, K. T. (2008). Squat-jump training at maximal power: Does it enhance sprint ability? *Journal of Strength and Conditioning Research, In press (due for publication mid 2008).*

(Chapter 6)

Training at a load maximising power output (Pmax) is an intuitively appealing strategy for enhancement of performance that has received little research attention. In this study we identified each subject's Pmax for an isoinertial resistance training exercise used for testing and training, then related the changes in strength to changes in sprint performance. The subjects were 18 well-trained rugby-league players randomised to two equi-volume training groups for a 7-week period of squat-jump training with heavy loads (80 %1RM) or with individually determined Pmax loads (20.0 - 43.5 %1RM). Performance measures were 1RM strength, maximal power at 55% of pre-training 1RM, and sprint times over 10- and 30-m. Percent changes were standardised to make magnitude-based inferences. Relationships between changes in these variables were expressed as correlations. Sprint times over 10 m showed improvements in the 80 %1RM group (-2.9 ±3.2%) and Pmax group (-1.3 ±2.2%), and there were similar improvements in 30-m sprint time (-1.9 ±2.8% and -1.2 ±2.0% respectively). Differences in the improvements in sprint time between groups were unclear, but improvement in 1RM strength in the 80 %1RM group (15 ±9%) was possibly substantially greater than in the Pmax group (11 ±8%). Small-moderate negative correlations between change in 1RM and change in sprint time ($r \sim$ -0.30) in the combined groups provided the only evidence of adaptive associations between strength and power outputs, and sprint performance. In conclusion, it appears that training at the load that maximises individual peak power output for this exercise with a sample of professional team-sport athletes was no more effective for improving sprint ability than training at heavy loads and the changes in power output were not usefully related to changes in sprint ability.