Title:	Validation of an optical encoder during free weight resistance movements and analysis of bench press sticking point power during fatigue
Creator:	Drinkwater, Eric J
Creator:	Galna, Brook
Creator:	McKenna, Michael J
Creator:	Hunt, P. H., Pyne, D. B.
Subject	Smith Machine, bench press, squat, kinetics, repetition failure
Publisher:	National Strength and Conditioning Association
Contributor:	CSU
Contributor:	Other
Contributor:	Other
Type	Journal Article
Identifier	http://nsca.allenpress.com/nscaonline/?request=get-abstract&doi=10.1519%2FR-20406.1
Rights:	Permission required (Sherpa White)
Abstract:	During the concentric movement of the bench press, there is an initial high-power push after chest contact, immediately followed by a characteristic area of low power, the so-called "sticking region." During high-intensity lifting, a decline in power can result in a failed lift attempt. The purpose of this study was to determine the validity of an optical encoder to measure power and then employ this device to determine power changes during the initial acceleration and sticking region during fatiguing repeated bench press training. Twelve subjects performed a free weight bench press, a Smith Machine back squat, and a Smith Machine 40-kg bench press throw for power validation measures. All barbell movements were simultaneously monitored using cinematography and an optical encoder. Eccentric and concentric mean and peak power were calculated using time and position data derived from each method. Validity of power measures between the video (criterion) and optical encoder scores were evaluated by standard error of the estimate (SEE) and coefficient of variation (CV). Seven subjects then performed 4 sets of 6 free weight bench press repetitions progressively increasing from 85 to 95% of their 6 repetition maximum, with each repetition continually monitored by an optical encoder. The SEE for power ranged from 3.6 to 14.4 W (CV, 1.0-3.0%; correlation, 0.97-1.00). During the free weight bench press training, peak power declined by approximately 55% ($p < 0.01$) during the initial acceleration phase of the final 2 repetitions of the final set. Although decreases in power of the sticking point were significant ($p < 0.01$), as early as repetition 5 (-40%) they reached critically low levels in the final 2 repetitions (>-95%). In conclusion, the optical encoder provided valid measures of kinetics during free weight resistance training movements. The decline in power during the initial acceleration phase appears a factor in a failed lift attempt at the sticking point.
Bibliographic Citation:	Journal of Strength and Conditioning Research, V21, No.2 pp. 510-517

Title: **Validation of an optical encoder during free weight resistance movements and analysis of bench press sticking point power during fatigue**

Running Head: Validity of an optical encoder

Conducted at: Australian Institute of Sport, Canberra, ACT, AUSTRALIA

Authors: Eric J. Drinkwater[1,2], Brook Galna[3], Michael J McKenna[2], Patrick H Hunt[4], David B Pyne[5]

Institutions: [1] School of Human Movement Studies, Charles Sturt University, Bathurst, New South Wales, Australia

[2] School of Human Movement, Recreation and Performance, Centre for Ageing, Rehabilitation, Exercise and Sport, Victoria University, Melbourne, Victoria, Australia

[3] Department of Biomechanics, Australian Institute of Sport, Canberra, ACT, Australia

[4] Basketball Australia, Sydney, Australia

[5] Department of Physiology, Australian Institute of Sport, Canberra, ACT, Australia

Corresponding Author:

Eric Drinkwater

School of Human Movement Studies

Charles Sturt University

Panorama Avenue

Bathurst, NSW

2795

Phone: +61 2 6338 4345

Fax: +61 2 6338 4065

edrinkwater@csu.edu.au

Submission Date: December, 2005

Revision Date: May, 2006

Validation of an optical encoder during free weight resistance movements and analysis of bench press sticking point power during fatigue

ABSTRACT

During the concentric movement of the bench press, there is an initial high-power push after chest contact, immediately followed by a characteristic area of low power, the so-called “sticking region”. During high-intensity lifting, a decline in power can result in a failed lift attempt. The purpose of this study was to determine the validity of an optical encoder to measure power, and then employ this device to determine power changes during the initial acceleration and “sticking region” during fatiguing repeated bench press training. Twelve subjects performed a free-weight bench press, a Smith Machine back squat, and a Smith Machine 40 kg bench press throw for power validation measures. All barbell movements were simultaneously monitored using cinematography and an optical encoder. Eccentric and concentric mean and peak power were calculated using time and position data derived from each method. Validity of power measures between the video (criterion) and optical encoder scores were evaluated by standard error of the estimate (SEE) and coefficient of variation (CV). Seven subjects then performed four sets of six free-weight bench press repetitions progressively increasing from 85 to 95% of their 6 repetition maximum, with each repetition continually monitored by an optical encoder. The SEE for power ranged from 3.6 to 14.4 W (CV, 1.0-3.0%; correlation, 0.97-1.00). During the free-weight bench press training, peak power declined by ~55% ($p<0.01$) during the initial acceleration phase of the final two repetitions of the final set. While decreases in power of the sticking point were significant ($p<0.01$) as early as repetition five (-40%) they reached critically low levels in the final two repetitions (>-95%). In conclusion, the optical encoder provided valid measures of kinetics during free-weight resistance training movements. The decline in power during the initial acceleration phase appears a factor in a failed lift attempt at the sticking point.

Key Words: Smith Machine, bench press, squat, kinetics, repetition failure

INTRODUCTION

For at least three decades investigators have been aware of the need for a high degree of specificity between the power output at which a subject trains and the power output at which the subject is tested [4]. Until recently, detailed analysis of power output during free-weight training has only been possible by using video or cinematographic analysis to derive velocity by measuring distance and time [2, 17]. Video analysis is a very labour and resource intensive method of analysis, limiting its utility as a research or practical tool for large scale power output data assessment collected over extended periods of time.

To overcome the labour intensive nature of video analysis in resistance training research, the testing and training of subjects is usually performed with isokinetic or isometric protocols [1, 14]. However, deriving practical recommendations for athletic training from this approach centers on resolving concerns of different recruitment patterns and mechanisms of fatigue inherent in different forms of contractions [7, 20]. The findings from these laboratory training protocols may not directly apply to athletes across a range of sports. Investigations intended to apply to athletes should ideally be conducted initially in the laboratory setting [1] and then transferred to the free-weight setting [19]. Unfortunately the degree of experimental control in the field often does not match that achieved in the laboratory. Even when research training programs employing free-weights attempt to control for training volume or intensity between training groups, there can be substantial differences between groups in total work performed, power output, or time under tension [5]. Therefore, an accurate method of monitoring long-term free-weight resistance training programs is essential to the application of resistance training research in an applied setting.

A number of well controlled research studies have assessed the kinetic analysis of the free-weight bench press, a very common free-weight resistance training lift [12, 24, 29]. Changes in bench press movement kinetics have been typically assessed by increasing the intensity of single repetitions [12, 29]. However, there is no analysis of how movement kinetics change as fatigue accumulates over a training set that consists of multiple sets and repetitions, typical of most resistance training programs [27]. Of particular interest is assessing changes in both overall power production during the full concentric movement, and in power production in each of the discrete phases of the concentric bench press movement [12, 29]. Since both fatigue [10] and movement kinetics [25] play determining roles in training outcomes, it is relevant for scientists to evaluate, and strength coaches to monitor, the changes that occur in movement kinetics as a result of fatigue.

The potential application of optical encoder technology in various training and research settings has spurred the development and release of several commercial devices. Recent research has utilized linear position transducers to measure power of movements such as bench press [21, 22], lunge [8], bicep curl [18] and vertical jump [6, 18]. While there is a large potential for these devices to improve the quality and control of resistance training research, limited data exists on their validity to measure power. To date only one study has validated this type of instrumentation against a criterion measure [8]. Cronin et al. [8] validated the Unimeasure™ optical encoder using a force plate to measure force output during ballistic jumping, but only measured ballistic movements on force-related properties, not power. The purpose of this research was therefore twofold. First, this study set out to evaluate the validity of the Gymaware™ linear position transducer to measure a variety of movement kinetics of the free-weight bench press, Smith machine bench press throw, and Smith machine back squat movements. Secondly, we sought to investigate changes in power output that occur over a typical, fatiguing free-weight bench press training session.

METHODS

Approach to the Problem

To assess the validity of the Gymaware™ optical encoder to measure power we assessed both concentric and eccentric mean and peak power output of 12 subjects while they performed Smith Machine back squats, Smith Machine bench press throw, and free-weight bench press, each on separate days. Each lift was simultaneously recorded using a video camera and an optical encoder. Video captures were later analyzed for time and position data from which power was calculated. Validity was evaluated using established statistical procedures. Validity of the optical encoder compared to video analysis was evaluated from the magnitudes of standard errors of the estimate (SEE) and coefficients of variation (CV). Relationships between the criterion (video) and optical encoders were quantified using Pearson Product Moment and expressed as an r value.

To investigate changes in power output that occur over a typical free-weight bench press training session, seven subjects performed four sets of six of free-weight bench press repetitions, while being continuously monitored using an optical encoder. Data collected from the optical encoder was then exported and peak power of the initial acceleration (i.e. first phase) and maximal strength (i.e. third phase) [12] for each repetition was quantified. Since the sticking point represents a phase of declining power, our analysis inspected the lowest power between the first and third phases. Since the fourth phase of the bench press represents another phase of declining power that inevitably ends in the bar stopping at the end of the concentric phase, no power analysis was conducted on this phase. Power changes in each phase were then analysed to quantify power changes over the 24 total repetitions in each phase relative to the first repetition.

Subjects

The sample group comprised 12 highly trained junior male basketball players (age 17.9 ± 0.6 y, height 198.4 ± 9.8 cm, body mass 97.5 ± 16.5 kg; 3RM squat 105.0 ± 13.8 kg; 3RM bench press 80.5 ± 8.4 kg, mean ± SD). All subjects had moderate to extensive weight training experience ranging from six months to beyond two years, including bench press and squat exercises. Subjects, and where appropriate (i.e. those subjects under 18 y of age) the subject's parents, provided written informed consent for testing, data collection, and publication of results as part of their Scholarship Agreement with the Australian Institute of Sport (AIS), in accordance with requirements of the AIS Ethics Committee. Testing and training procedures were explained before the start of the study and subjects were informed that they could withdraw from testing at any time without prejudice.

Procedures

Lifts Evaluated

Subjects were evaluated performing a single repetition of their 3RM on a free-weight bench press, a Smith Machine back squat, and a 40 kg Smith Machine bench press throw, each on separate days. Data for each lift was simultaneously collected using an optical encoder and digital video. For the free-weight bench press, subjects completed a warm up involving 10 min of stationary cycling and three sets of free-weight bench press comprising 12 repetitions at 20 kg, 6 repetitions at 30 kg, and 3 repetitions at 40 kg with 1 min rest between sets. Free-weight bench press repetitions were then evaluated according to established criteria [11]. Briefly, athletes lowered the bar until the chest was touched lightly approximately 3 cm superior to the xiphoid process. The elbows were extended equally with the head, hips, and feet remaining in contact with the bench throughout the lift. Previously documented 3RM test records were used as a guide for selecting the resistance.

For the Smith Machine back squats, subjects completed a warm up involving 10 min of stationary cycling and three sets of back squats comprising 8 repetitions at 40 kg, 6 repetitions at 60 kg, and 3 repetitions at 70 kg with 1 min rest between sets. Squats were also evaluated according to established criteria [11]. Briefly, subjects supported the bar above the posterior deltoids at the base of the neck. Athletes slowly flexed the knees and hips, lowering the bar until the front of the thighs were parallel with the ground. Heels of the feet remained flat on the ground while the back remained flat and the head level to keep the force on knee and hip flexion and extension. Previously documented 3RM test records were used as a guide to select the resistance.

On a separate day to the free-weight bench press and squat testing, subjects were evaluated for maximal power output during a 40 kg Smith Machine bench press throw. Prior to testing each subject completed a thorough warm-up involving 10 min of stationary cycling and three sets of free-weight bench press comprising 12 repetitions at 20 kg, 6 repetitions at 30 kg, and 3 repetitions at 40 kg with 1 min rest between sets. Subjects then performed two individual 40kg bench press throws, separated by at least one minute [10]. Athletes lowered the bar until the chest was touched lightly approximately 3 cm superior to the xiphoid process. The elbows were extended equally with the head, hips, and feet remaining in contact with the bench throughout the throw. The subject held the bar on the chest for 2 s before ballistically throwing the bar as high as possible.

Optical Encoder

The displacement and time between data points of each bench press and squat repetition was measured with a Gymaware™ optical encoder (Kinetic Performance Technology, Canberra, Australia). This commercially available device consists of a floor unit, made up of a spring powered retractable cord which passes around a pulley mechanically coupled to an optical encoder (Figure 1). The end of the cord in turn attaches to the barbell. The floor unit was positioned on the floor perpendicular to the movement of the barbell. The microprocessor in the floor unit (Figure 1) calculates velocity and distance of the barbell from the spinning movement of the pulley. The device gave one pulse approximately every 3 mm of load displacement, with each displacement value time-stamped with a 1 ms resolution. The position - time data, generated at a maximum rate of 25 Hz, is sent via a fixed wire from the floor unit to an infra-red transceiver (Figure 1). The infra-red transceiver sends the position - time data by infra-red signal to a personal digital assistant (PDA, Model: Tungsten-e, Palm, Milpitas, CA). The mass of the bar, entered into the PDA by the Gymaware™ operator, the entire displacement (mm) of the barbell, and time (ms) for the movement were used to calculate mean values for power (see calculations 1 through 7). The interaction of the floor unit with the barbell, the attachment of the floor unit to the infra-red transceiver, and the location of the infra-red transceiver to communicate with the personal digital assistant are illustrated in Figure 2.

Digital Video Recording

A digital video camera (Sony – Digital Video Recorder DRC-TRV900E PAL) was used to film each lift for each subject at 50Hz. The camera was placed perpendicular to the front of the bar to record the vertical aspect of the movement. The camera was placed at a horizontal distance of 8 m from the bar to minimize the parallax effect. A reflective marker was placed at the same point as the attachment point of the optical encoder on the bar to digitally track the movements of the bar. A second reflective marker was placed on the lifting apparatus frame to establish a stable point of reference. An image of the lifting apparatus with a vertical calibration pole marked in 0.10 m increments was captured before the start of each testing session. The vertical calibration pole established a distance scale to quantify the vertical displacement of the bar against but does not represent the sensitivity of the measurement.

Time and position data were generated with Ariel Performance Analysis System (APAS) motion analysis software (Ariel Dynamics, Inc. Trabuco Canyon, CA) [28]. The vertical calibration poles that provided scale for the frame size were digitized every 0.2m vertically either side of the capture volume. The reflective marker was then digitised using the APAS ‘auto-digitize’ function. The data was unfiltered. Every second frame of data was analysed, resulting in a 25 Hz capture rate in order to compare more closely with the optical encoder time-event encoder sample rate of approximately 25 Hz.

External power was calculated from Gymaware and video time-position data separately through several stages. First, displacement was calculated as the change in position in the vertical plane (1):

$$d = \Delta p \tag{1}$$

where d is displacement, p is position (m).

Velocity was then calculated as displacement over change in time (2):

$$v = d/\Delta t \tag{2}$$

where v is velocity ($m.s^{-1}$) and t is time (s).

Interpolation was used to shift velocity to match the existing time code. To interpolate velocity, the time that the known velocities occurred was calculated (3):

$$t_{vn} = (t_{n-1} + t_n)/2 \text{ and } t_{vn+1} = (t_n + t_{n+1})/2 \tag{3}$$

where t_{vn} is the time at velocity and n is the frame number.

The gradient of two known consecutive velocities was then calculated (4):

$$a_n = (v_{n+1} - v_n)/(t_{vn+1} - t_{vn}) \tag{4}$$

where a_n is the gradient of the two velocities ($m.s^{-2}$).

Velocity at t_n was then calculated by adding v_n to the product a_n and t_{vn} (5):

$$v_{tn}= v_n +(a_n t_{vn}) \tag{5}$$

Interpolation was also used to match acceleration to the same time code as velocity in the above fashion. Force was then calculated as the product of mass (of the bar) and acceleration (of the bar and gravity) (6):

$$F= m\ (a_{gravity}+a_{bar}) \tag{6}$$

where F is force (N), m is mass (kg), $a_{gravity}$ is acceleration due to gravity ($m.s^{-2}$), and a_{bar} is the acceleration of the bar ($m.s^{-2}$).

Power was then calculated as the product of force and velocity (7):

$$P=Fv \tag{7}$$

where P is power (W), F is force (N), and v is velocity ($m.s^{-1}$).

Training Session

The training session was similar to that used previously by our group [10]. Briefly, training involved seven subjects undertaking four sets of six free-weight bench presses, with each set commencing every 2 min and 45 s, at intensities of 85, 90, 95, and 95% of the individual's 6RM, in sets one to four, respectively. All repetitions were recorded on the PDA for analysis of changes in kinetics over the training protocol. Files were exported from the Gymaware software and visually inspected for changes within each of the four phases of the free-weight bench press as identified by Elliot et al [12]. Mean concentric power for each complete repetition was also analyzed for changes over the course of the training session.

Statistical Analyses

Only the validity of the concentric peak and mean power was analysed for the Smith Machine bench press throw, while the validity of both the concentric and eccentric power was assessed for the free-weight bench press and Smith Machine back squat. Differences between the two methods of measurement (optical encoder and digital video) are expressed as a standard error of the estimate (SEE) and coefficient of variation (CV). Correlations between the two scores were calculated using Pearson Product Moment and expressed as an r value. For each lift, mean differences between measures collected from the optical encoder and power calculated from the video analysis were determined and expressed with 95% confidence limits (95%CL) to establish the precision of the estimate.

The practical significance of differences between criterion and practical measures was based on the smallest worthwhile difference with a small standardized (Cohen) effect size (>0.2), derived by dividing the mean difference by the between-subject standard deviation (SD) [3]. Chances of a substantial true difference were estimated with a spreadsheet and interpreted qualitatively as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; 25-75%, possible; >75%, likely; >95%, very likely; >99% almost certain [16, 23, 26]. Effects sizes of 0.6 and 1.2 were interpreted as thresholds for moderate and large effects respectively, as suggested for testing of team-sport athletes [15].

In order to investigate the changes that occur in free-weight bench press power over the single training session, we visually inspected data exported from the Gymaware software for areas of increasing and decreasing power. Once these areas were identified, we evaluated peak power as the point of highest power within that region. Since we were interested in assessing the accumulating effect of fatigue over the entire training session, we used the first repetition of the first set as the point of reference to evaluate changes that occurred in all subsequent repetitions. Power of each phase of the concentric movement (i.e. first, second, and third) were compared between the first repetition with subsequent repetitions (i.e. 2 to 24) to investigate changes in power over the entire training session. Comparisons were also made between the first repetition of each set (i.e. 1, 7, 13, and 19) and subsequent repetitions within that set to investigate within-set changes in power. Finally, mean power of the entire concentric phase of each repetition was also assessed over the training set and within each set. Comparisons were made using a two-way ANOVA with repeated measures and Tukey HSD post hoc analysis. Significance was accepted at $p<0.05$.

RESULTS

Validity

The validity of power measurements using the optical encoders for the specific free-weight movements expressed with 95% confidence limits are shown in Table 1. The SEE for all movements, expressed as a CV, were ≤3.0% and ranged from 3.6 to 14.4 W in absolute terms. The r-value derived from the correlation analysis between the optical encoder and video analysis were ≥0.97 for all measures of power on all lifts ($p<0.01$). We estimated that there is almost no probability that true differences between the criterion and practical measures are likely to meaningful in performance research (Table 1). Of the ten measurements evaluated, the only measure that showed a difference that was practically meaningful was the peak eccentric bench press power.

Training Session

Typical Examples

The different phases of the free-weight bench press are illustrated graphically in a typical example shown in Figures 3 and 4. Figure 3 illustrates a single repetition of a subject at 95% 6RM prior to beginning the training session. Figure 4 illustrates a single repetition of the same subject lifting 95% 6RM after the exhaustive training session. Both figures show an initial rise and fall in power prior to the eccentric portion of the free-weight bench press movement. This profile indicates the barbell is moving from its resting position in the bench rack into the ready position. Next, there is an increase in power, indicating the eccentric movement of the lift. The power then decreases before increasing again corresponding with the bar reaching the subject’s chest and beginning of the concentric movement of the lift. During the concentric movement, power shows an initial spike (first phase) before decreasing into the sticking point (second phase). The subject has pressed through the sticking point when power begins increasing again to the repetition's peak power (third phase). Finally power begins decreasing again to finish the concentric phase (fourth phase). The erratic power after the forth phase represents the subject's placing of the barbell back into its resting position. Once the exhaustive training session was completed (Figure 4), there is much lower power in the second and third phases and the second phase becomes longer.

Mean power per repetition (Phases 1-4)

When compared to repetition 1, mean power for each concentric movement (Phases 1-4 inclusive) had decreased significantly by repetition 6 (-27%, $p<0.01$), 12 (-24%, $p<0.01$), and 17 to 24 (-19 to -61%, $p<0.03$) (Figure 5). Power decrements were also significant within each set at repetition 6 in set 1 (-27%, $p<0.01$), repetition 6 in set 2 (-28%, $p<0.01$), repetition 5 and 6 of set 3 (-29 and -42%, $p<0.01$), and repetitions 4 to 6 of set 4 (-27 to -51%, $p<0.01$) (Figure 5). Clearly the decrement in power was evident earlier within the set of 6 repetitions as the session progressed.

Peak power – first phase

In each free-weight bench press repetition there was an identifiable initial phase in which power peaked quickly as the subject pressed the bar off their chest (Figure 3). Peak power exerted during the first phase was only lower than repetition 1 at repetitions 22, 23 and 24 (-27, -52 and -60%, all $p\leq 0.01$) (Figure 6). There were also within set reductions in power at repetitions 5 and 6 of set 4 (-50 and -58%, both $p<0.01$).

Low power – second ('sticking point') phase

The next phase of the free-weight bench press, the so-called sticking point, was characterized by declining power after the initial power spike (Figure 3). The lowest power measured during the sticking point was lower than that of repetition 1 in repetitions 5 and 6 (-40 and -58%), 11 and 12 (41 and 52%), 15 to 18 (-40 to -72%), and 20 to 24 (45 – 100%, all p<0.01, Figure 7). Within-set decrements were also observed in repetitions 5 and 6 of set 1 (-40 and -58%, p<0.01), 5 and 6 of set 2 (-36 and -48%, p<0.04 and p<0.01 respectively), 5 and 6 of set 3 (-59 and -66%, p<0.01), and 4 to 6 of set 4 (-60 to -100%, p<0.01).

Peak power – third phase

After the sticking point was overcome, there was a third phase of secondary high power. There was a significant decrease in peak power during the third phase from repetition 1 to repetitions 6 (-33%, p<0.01), 12 (-39%, p<0.01), 16 to 18 (-25 to -48%, p<0.01), and 21 to 24 (-28% to -58%, p<0.01, Figure 8). There were also substantial decrements in power at repetitions 6 of set 1 (-33%, p<0.01), 5 and 6 of set 2 (-21 and -43%, p<0.01), 3 to 6 of set 3 (-21 to -50%, p<0.02), and 4 to 6 of set 4 (-40 to -53%, p<0.01).

DISCUSSION

The major conclusion of the study is that the Gymaware™ optical encoder is a valid method of collecting kinetic data on resistance training movements, based on the low CV and SEE derived from the video (criterion) and optical encoder. The second important finding was the decline in mean power over the full concentric movement and decline in peak power at each of the concentric phases, during a high-intensity free-weight bench press single training session. The initial phase of the concentric movement was relatively fatigue resistant compared to the second and third phases, illustrated by the peak power output during the sticking point of the free-weight bench press not approaching zero until after there was a significant drop in power in the first phase. These data suggest a direct link between the decline in initial production of power with fatigue and the subsequent ability to breech the sticking point in the standard free-weight bench press.

The study has demonstrated that use of optical encoders is a valid method of evaluating both peak and mean power in a variety of resistance training movements, with a low CV of 1-3% and high r-values of 0.97 to 1.00 for nine out of the ten measurements evaluated. The only measurement that showed a substantial practical difference between the optical encoder and video-derived power calculations was the peak eccentric free-weight bench press power. This difference in eccentric power is likely accounted for by the two-dimensional analysis of video, while the optical encoder was presumably able to detect movements in all three dimensions. The optical encoder detected movement in the horizontal plane during the eccentric phase that could not be detected on the two-dimensional analysis of the video analysis. This effect would only be present during the free-weight bench press since this lift was the only one that did not restrict movement through the horizontal plane in the Smith Machine. In this respect, the optical encoder was able to detect movement that even the criterion digital video analysis was unable to detect.

Kinetic analyses over the four training sets indicated that peak power output in three of the four phases of the free-weight bench press, and overall mean power of the concentric movement, were substantially depressed as the four sets of six repetitions progressed. Decrements in peak power in the second (Figure 7) and third phase (Figure 8) were evident as early as the first set, but peak power during the first phase only started to decrease late in the fourth set (Figure 6), thus indicating the relative fatigue resistance of the first phase. Of particular interest was the finding that the repetitions where the peak power of the second phase approached zero (i.e. repetition failure) was the only repetitions in which the first phase peak power was also significantly lower than the first repetition. Power production during the second and third phases of each repetition is presumably dependent on voluntary activation of cross-bridge cycling of the active muscle groups, whereas power production during the first phase involves both voluntary activation and the stretch-shortening cycle, given that it is immediately preceded by the eccentric movement. Consequently any impairment in voluntary force development during the first phase would have a lesser effect on peak power output as this would theoretically be compensated for by the relatively fatigue resistant stretch-shortening mechanisms [13]. The second and third phases of the concentric movement would be entirely dependent on voluntary activation of the required muscle groups, which explains their greater susceptibility to fatigue. Only when involuntary stretch-shortening cycle components begin to fatigue and are no longer adequately compensating for the dramatic impairment of voluntary force would peak power during the first phase decrease [12]. Since the first phase immediately precedes the sticking point and can dramatically add to the forced generation capability [9], the loss of power during the first phase leads to an inability to push through the sticking point. Therefore, repetition failure may be a key component to periodized strength training programs by training the capacity to generate enough power in the first phase to push through the sticking point [10].

In conclusion, we have shown that the Gymaware™ optical encoder provides a valid measure of power in a standard weight room setting. We have also described changes in power output that occur over a typical free-weight bench press training session. Of particular interest was the relationship of power loss between the first versus the second and third phases of the free-weight bench press. The second and third phases were particularly sensitive to fatigue, evidenced by a substantial early decline in power. In contrast the first phase was relatively fatigue resistant, likely as a result of the contribution of the stretch-shortening cycle compensating for loss of voluntary force production. Once significant power is lost in the first phase, the loss of power during the sticking region becomes substantial enough to make task failure probable.

PRACTICAL APPLICATIONS

The optical encoder is a portable device that provides valid measures of peak and mean power. Sport scientists could easily utilise optical encoders to analyse these training variables, in addition to the volume of work performed, during free-weight resistance training. These applications will help the sport scientist to, firstly, design studies with greater control over training variables to improve the quality of free-weight training research, and secondly, identify the mechanisms that underpin the acute responses and longitudinal changes to discrete training programs. Continuous monitoring of training could assist the strength and conditioning coach to more effectively modify strength and power programs. The capacity of Gymaware™ optical encoders to store accurate data over long periods of time is also a practical advantage to conditioning coaches. Coaches will be able to monitor the progress of athletes in performance variables such as power or movement velocity.

An additional application of this research for conditioning coaches is the understanding that movement kinetics change as fatigue progresses. Early power decrements of power in the third phase of the free-weight bench press indicate accumulating impairment of the voluntary component of the concentric movement of free-weight bench press. In contrast, power decrements occurring in the first phase presumably reflect additional impairment of the components of the stretch shortening cycle. Since the only significant declines in power of the first phase correspond with the level of power at the sticking point approaching zero (i.e. repetition failure), training to repetition failure is implicated in stimulating adaptation of the first phase to generate greater power.

References

1. BEHM, D.G. and SALE, D.G. Intended rather than actual movement velocity determines velocity-specific training response. *J. Appl. Physiol.* **74**: 359-368. 1993.
2. CANAVAN, P.K., GARRETT, G.E., and ARMSTRONG, L.E. Kinematic and kinetic relationships between an Olympic-style lift and the vertical jump. *J. Strength Cond. Res.* **10**: 127–130. 1996.
3. COHEN, J. *Statistical power analysis for the behavioral sciences*. 2nd ed. Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1988.
4. COYLE, E.F., FEIRING, D.C., ROTKIS, T.C., COTE, R.W., 3RD, ROBY, F.B., LEE, W., and WILMORE, J.H. Specificity of power improvements through slow and fast isokinetic training. *J. Appl. Physiol.* **51**: 1437-1442. 1981.
5. CRONIN, J. and CREWTHER, B. Training volume and strength and power development. *J. Sci. Med. Sport*. **7**: 144-155. 2004.
6. CRONIN, J., HING, R., and MCNAIR, P. Reliability and validity of a linear position transducer for measuring jump performance. *J. Strength Cond. Res.* **18**: 590-593. 2004.
7. CRONIN, J., MCNAIR, P., and MARSHALL, R. Is velocity-specific strength training important in improving functional performance? *J. Sports Med. Phys. Fitness*. **42**: 267-273. 2002.
8. CRONIN, J., MCNAIR, P.J., and MARSHALL, R.N. Lunge performance and its determinants. *J. Sports Sci.* **21**: 49-57. 2003.
9. CRONIN, J.B., MCNAIR, P.J., and MARSHALL, R.N. The role of maximal strength and load on initial power production. *Med. Sci. Sports Exerc*. **32**: 1763-1769. 2000.
10. DRINKWATER, E.J., LAWTON, T.W., LINDSELL, R.P., PYNE, D.B., HUNT, P.H., and MCKENNA, M.J. Training leading to repetition failure enhances bench press strength gains in elite junior athletes. *J. Strength Cond. Res*. **19**: 382-388. 2005.
11. EARLE, R. and BARCHLE, R. Resistance Training and Spotting Techniques, in *Essentials of Strength Training and Conditioning*, R. Earle, ed. Chanpaign, Il. Human Kinetics, 2000. pp. 343-394.
12. ELLIOT, B., WILSON, G., and KERR, G. A biomechanical analysis of the sticking region in the bench press. *Med. Sci. Sports Exerc*. **21**: 450-462. 1989.
13. ENOKA, R.M. *Neuromechanic of human movement*. 3rd ed. Champagin, Il: Human Kinetics, 2002.
14. FOLLAND, J., IRISH, C., ROBERTS, J., TARR, J., and JONES, D. Fatigue is not a necessary stimulus for strength gains during resistance training. *Br. J. Sports Med.* **36**: 370-374. 2002.
15. HOPKINS, W.G. How to interpret changes in an athletic performance test. *Sportscience*. **8**: 1-7, sportsci.org/jour/04/wghtests.htm. 2004.
16. HOPKINS, W.G. Probabilities of clinical or practical significance. *Sportscience*. **6**: sportsci.org/jour/0201/wghprob.htm. 2002.
17. HOWELL, A.K., GAUGHAN, J.P., CAIRNS, M.A., FAIGENBAUM, A.D., and LIBONATI, J.R. The effect of muscle hypoperfusion-hyperemia on repetitive vertical jump performance. *J. Strength Cond. Res.* **15**: 446–449. 2001.

18. JENNINGS, C.L., VILJOEN, W., DURANDT, J., and LAMBERT, M.I. The reliability of the FitroDyne as a measure of muscle power. *J. Strength Cond. Res*. **19**: 859-863. 2005.
19. JONES, K., HUNTER, G., FLEISIG, G., ESCAMILLA, R., and LEMAK, L. The effects of compensatory acceleration on upper-body strength and power in collegiate football players. *J. Strength Cond. Res*. **13**: 99-105. 1999.
20. KAY, D., ST CLAIR GIBSON, A., MITCHELL, M.J., LAMBERT, M.I., and NOAKES, T.D. Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. *J. Electromyogr. Kinesiol.* **10**: 425-31. 2000.
21. LAWTON, T., CRONIN, J., DRINKWATER, E., LINDSELL, R., and PYNE, D. The effect of continuous repetition training and intra-set rest training on bench press strength and power. *J. Sports Med. Phys. Fitness*. **44**: 361-367. 2004.
22. LAWTON, T.W., CRONIN, J.B., and LINDSELL, R.P. Effect of interrepetition rest intervals on weight training repetition power output. *J. Strength Cond. Res*. **20**: 172-176. 2006.
23. LIOW, D. and HOPKINS, W. Velocity specificity of weight training for kayak sprint performance. *Med. Sci. Sports Exerc*. **35**: 1232-1237. 2003.
24. NEWTON, R.U., KRAEMER, W.J., HÄKKINEN, K., HUMPHRIES, B.J., and MURPHY, A.J. Kinematics, kinetics, and muscle activation during explosive upper body movements. *J. Appl. Biomech.* **12**: 31-43. 1996.
25. PEREIRA, M.I. and GOMES, P.S. Movement velocity in resistance training. *Sports Med*. **33**: 427-438. 2003.
26. PETERSEN, C.J., WILSON, B.D., and HOPKINS, W.G. Effects of modified-implement training on fast bowling in cricket. *J. Sports Sci*. **22**: 1035-1039. 2004.
27. RHEA, M.R., ALVAR, B.A., BURKETT, L.N., and BALL, S.D. A Meta-analysis to determine the dose response for strength development. *Med. Sci. Sports Exerc*. **35**: 456-464. 2003.
28. STUELCKEN, M.C., PORTUS, M.R., and MASON, B.R. Off-side front foot drives in men's high performance cricket. *Sports Biomech*. **4**: 17-35. 2005.
29. WILSON, G.J., ELLIOT, B.C., and KERR, G.K. Bar path and force profile characteristics for maximal and submaximal loads in the bench press. *Int. J. Sport Biomech.* **5**: 390-402. 1989.

Acknowledgements

The study results do not constitute endorsement of Gymaware™ optical encoders by the authors or the NSCA. We acknowledge the cooperation of the coaches and athletes from the Australian Institute of Sports Men’s Basketball Program.

Figure 1 – The Gymaware™ optical encoder floor unit. Number 1 indicates the retractor cord that attaches to the external load. Number 2 shows the pulley around which the retractor cord wraps. Number 3 indicates the optical encoder that sends a pulse to the microprocessor every 3 mm of rotation. Number 4 shows the retractable cable assembly that stores the retractor cord when the device is in the retracted position. Number 5 indicates the microprocessor and interface circuit that translates pulse information into position and velocity data. Number 6 indicates the infra-red transceiver that communicates with the personal digital assistant (PDA) to store data.

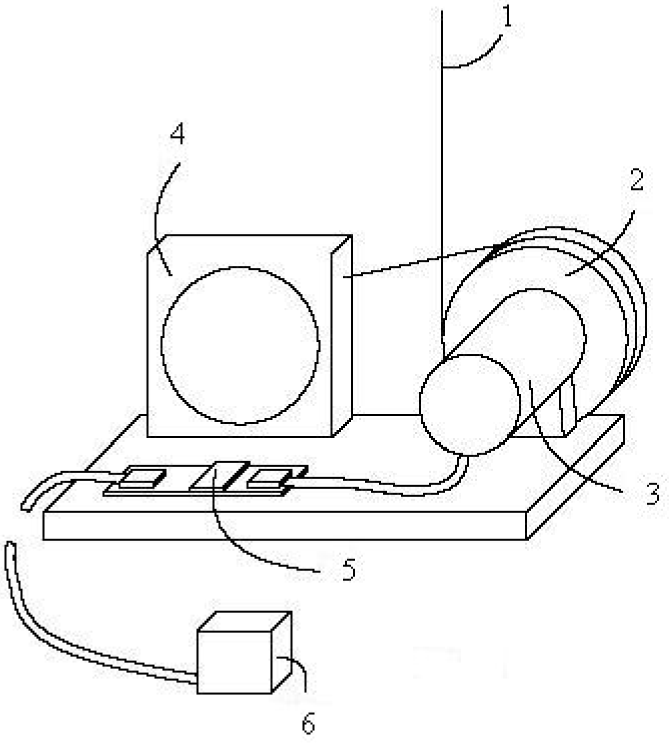

Figure 2 – Photograph of the Gymaware setup on a free-weight bench press, showing the cord attaching to the barbell (1) to the floor unit (2), the floor unit wired to the infra-red transceiver (3), which then transfers the position – time data to the personal digital assistant (4) via infra-red signal.

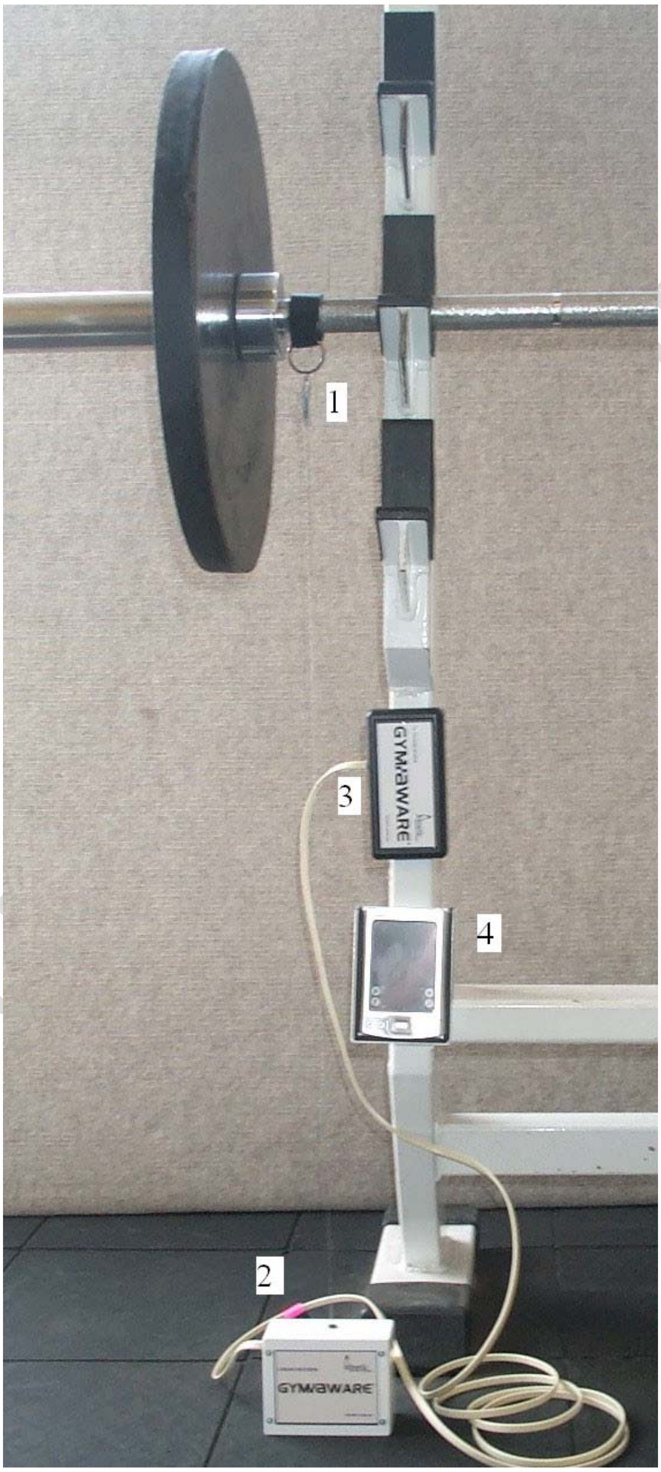

Figure 3 – Typical output from the Gymaware™ software of a free-weight bench press repetition illustrating power output (W) during a repetition in an unfatigued subject. Phases of the bench press are labelled as 1st for the initial portion of the concentric phase, 2nd as the 'sticking point', 3rd as the second high power region, and 4th as the area of deceleration as the concentric phase ends.

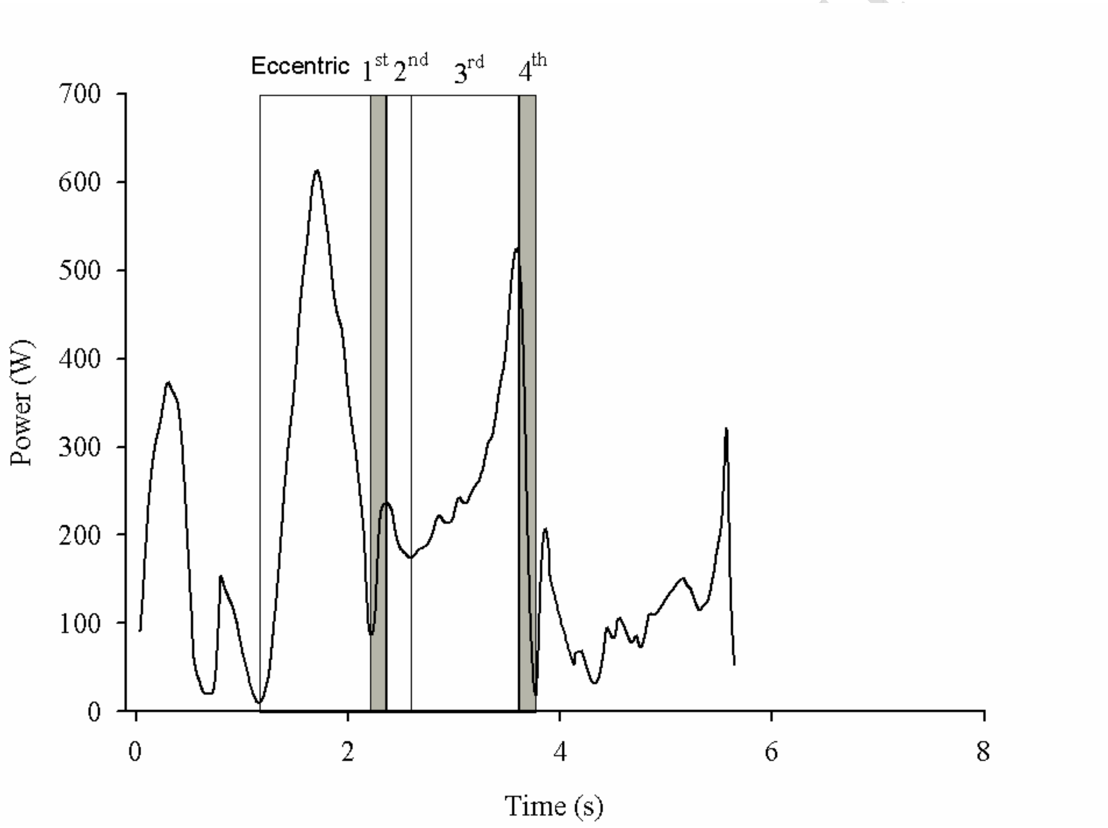

Figure 4 – Typical output from the Gymaware™ software of a free-weight bench press repetition illustrating power output (W) during a repetition in a highly fatigued subject. Phases of the bench press are labelled as 1st for the initial portion of the concentric phase, 2nd as the 'sticking point', 3rd as the second high power region, and 4th as the area of deceleration as the concentric phase ends.

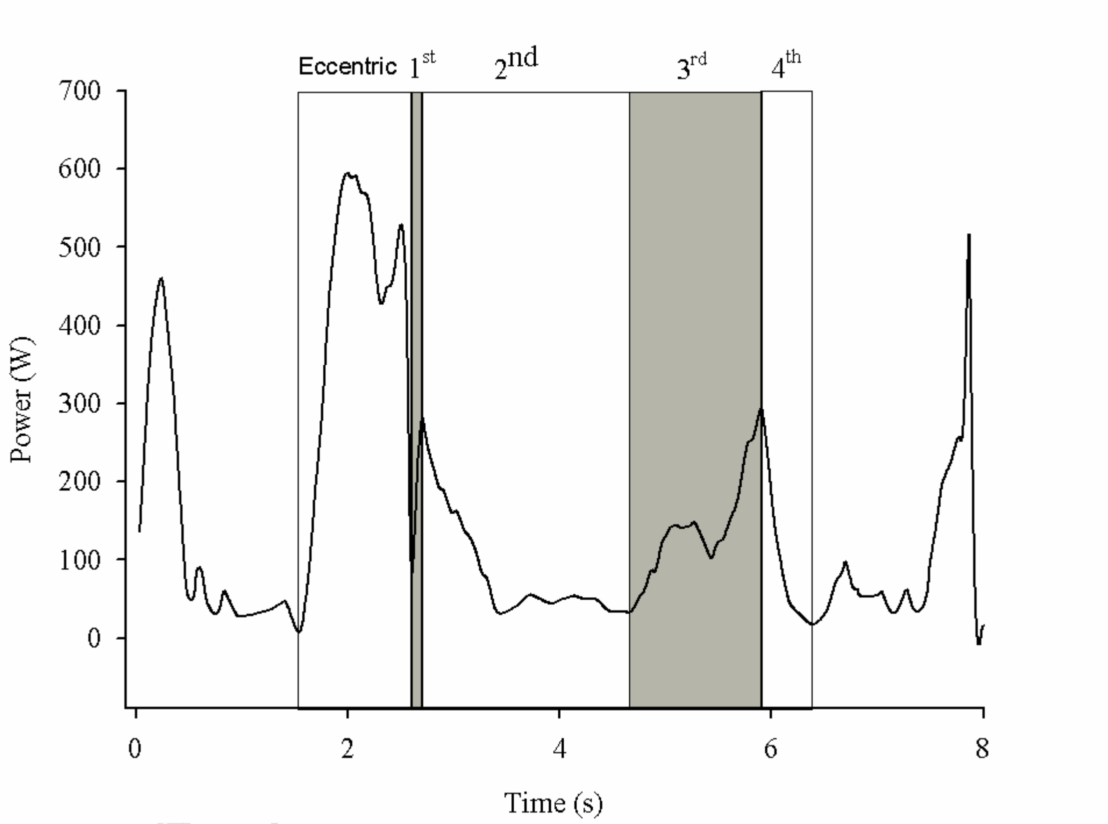

Figure 5 – Kinetic analysis of mean power ± SD (n=7) of the full concentric movement of the bench press (Phase 1-4) over 24 total repetitions divided into four sets of six repetitions. * and # = mean power lower than repetition 1 ($p<0.01$ and $p<0.03$ respectively); + = lower mean power than the first repetition within that set ($p<0.01$).

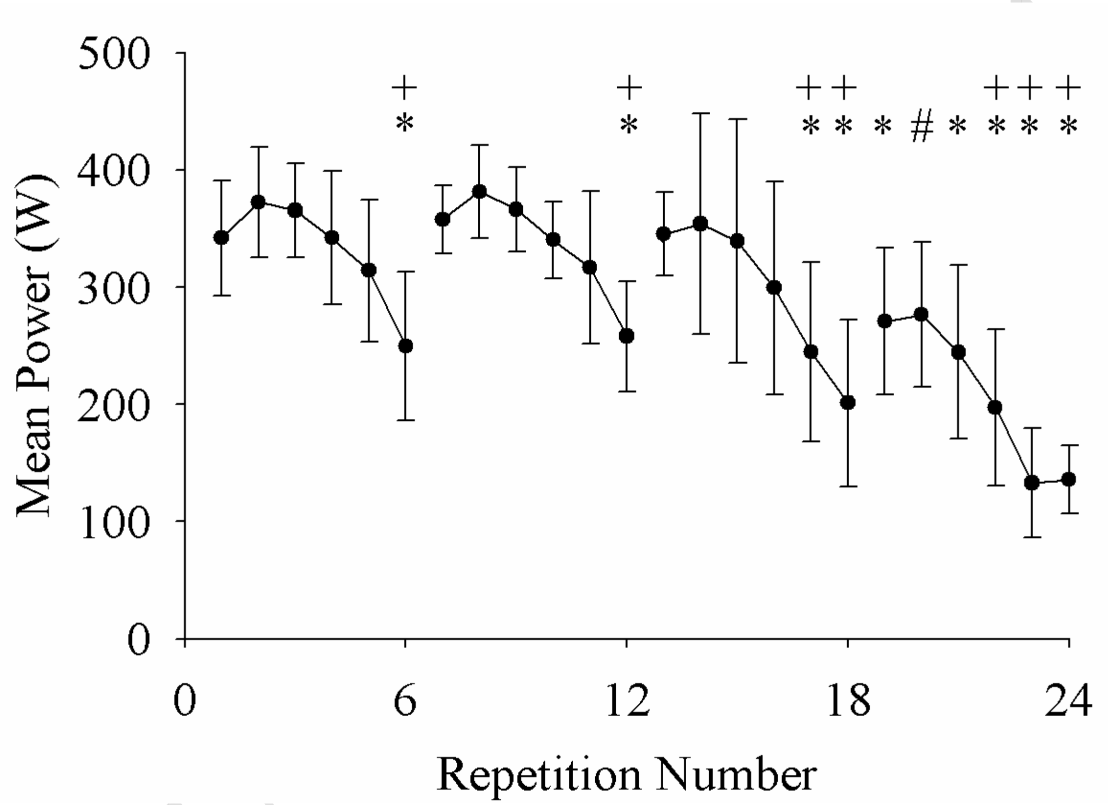

Figure 6 - Kinetic analysis of peak power ± SD (n=7) exerted during the first phase of the concentric movement of the bench press over 24 total repetitions divided into four sets of six repetitions. * = mean power lower than repetition 1 (p≤0.01); + = lower mean power than the first repetition within that set (p<0.01).

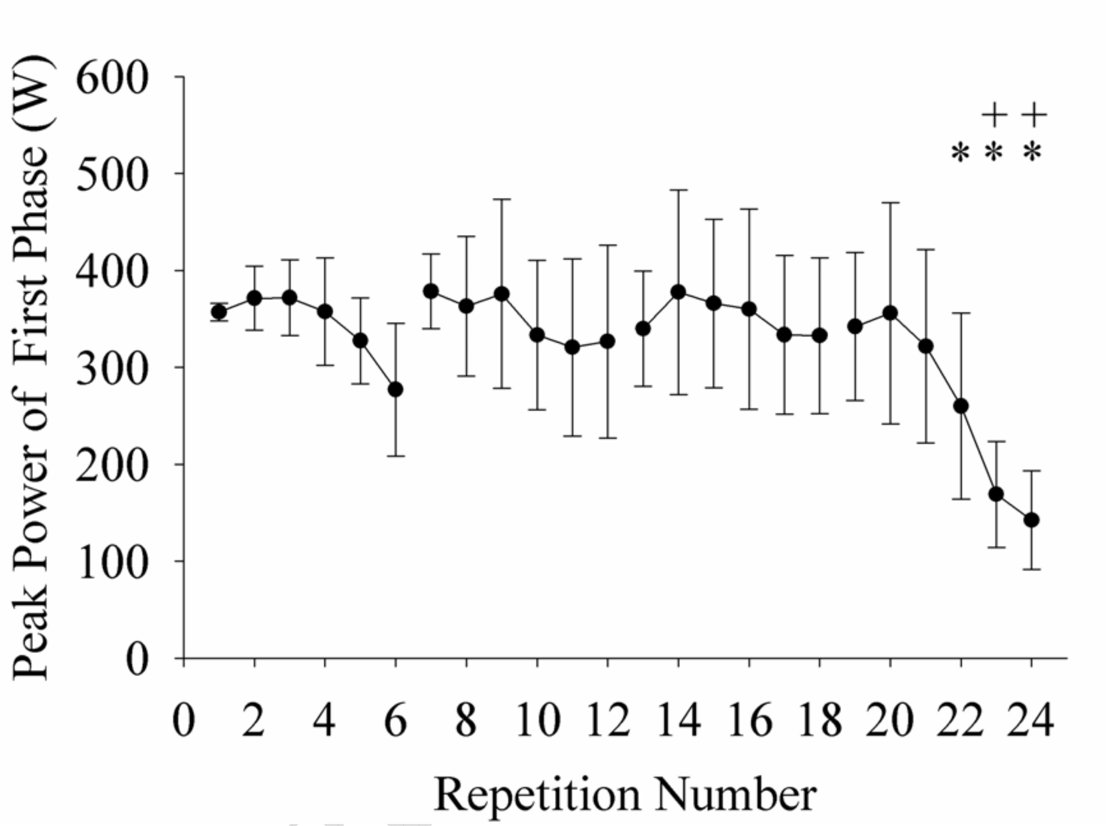

Figure 7 - Kinetic analysis of lowest power ± SD (n=7) exerted during the second ('sticking point') phase of the bench press over 24 total repetitions divided into four sets of six repetitions. * = mean power lower than repetition 1 ($p<0.01$); + and # = lower mean power than the first repetition within that set ($p<0.01$ and $p<0.04$ respectively).

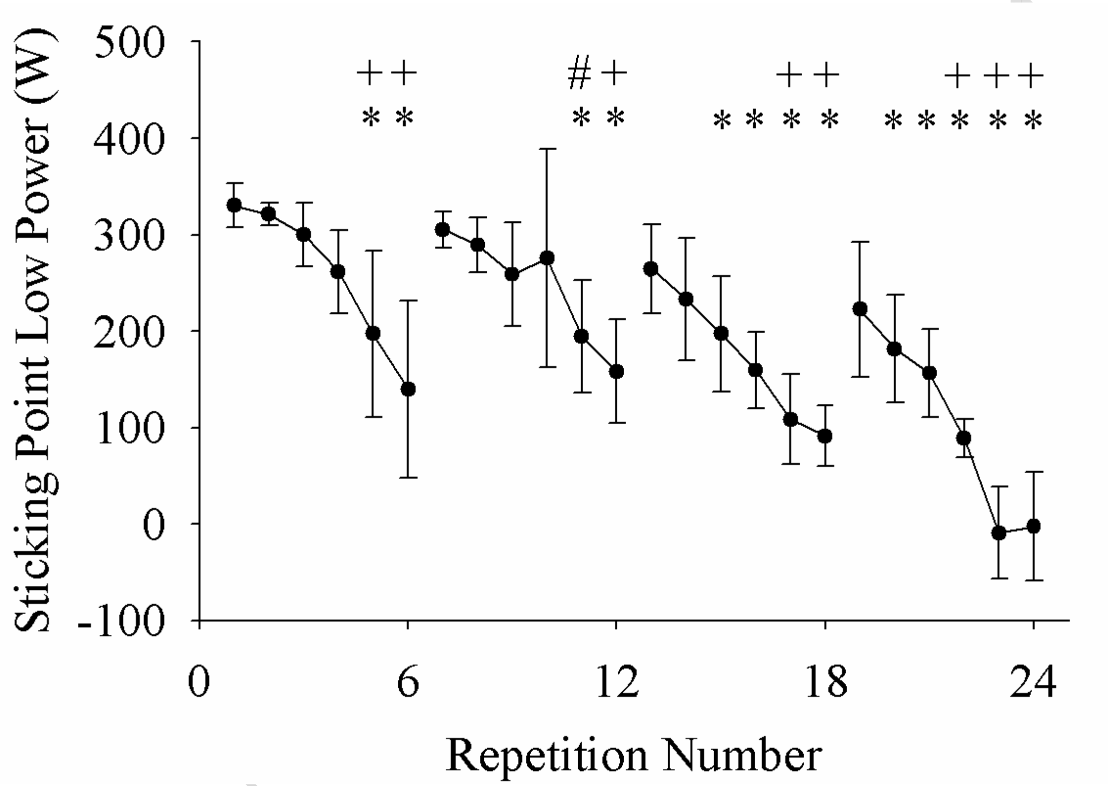

Figure 8 - Kinetic analysis of peak power ± SD (n=7) exerted during the third phase of the concentric movement of the bench press over 24 total repetitions divided into four sets of six repetitions. * = mean power lower than repetition 1 ($p<0.01$); + and # = lower mean power than the first repetition within that set ($p<0.01$ and $p<0.02$ respectively).

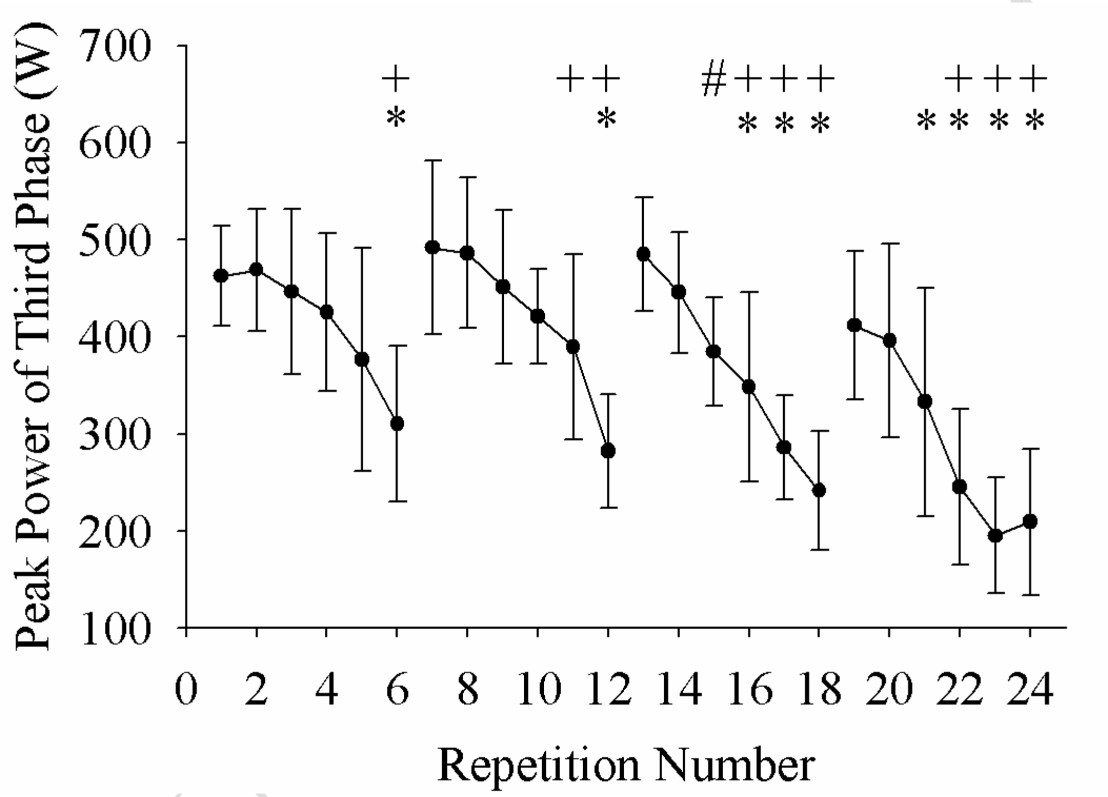

Table 1 - Validity of Gymaware™ optical encoder power calculation compared with video (criterion measure) power calculations (n=12).

Movement	Absolute Power (W, mean±SD)	Standard error of estimate			Coefficient of Variation			Pearson r[b]	Probability (%) of difference being clinically meaningful[c]
		Absolute (W)	Lower[a]	Upper[a]	%	Lower[a]	Upper[a]		
Squat mean eccentric	334 (±116)	3.6	2.3	7.9	1.16	0.75	2.57	1.00	0, almost certainly not
Squat mean concentric	372 (±111)	4.1	2.6	8.9	1.08	0.70	2.38	1.00	0, almost certainly not
Squat peak eccentric	607 (±228)	11.2	7.2	24.6	1.43	0.92	3.15	1.00	0, almost certainly not
Squat peak concentric	755 (±271)	14.4	9.3	31.7	2.16	1.39	4.75	1.00	0, almost certainly not
Throw mean concentric	368 (±43)	10.8	7.3	20.6	2.78	1.88	5.33	0.97	0, almost certainly not
Throw max concentric	727 (±128)	14.0	10.0	23.9	1.85	1.33	3.17	0.99	0, almost certainly not
Bench mean eccentric	328 (±68)	7.1	3.2	11.2	2.27	1.50	4.62	0.99	1, very unlikely
Bench mean concentric	253 (±38)	3.7	2.4	8.1	1.50	0.97	3.30	1.00	1, very unlikely
Bench peak eccentric	553 (±125)	7.8	5.2	15.9	1.33	0.88	2.70	1.00	32, possibly
Bench peak concentric	435 (±119)	13.2	8.7	26.9	3.02	2.00	6.16	0.99	0, almost certainly not

[a] *Lower and Upper refer to lower and upper confidence limits for the mean estimate of the SEE and CV*

[b] *All Pearson r p-values <0.01*

[c] Thresholds for assigning qualitative terms to chances of substantial effects were as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; <50%, possibly not; >50%, possibly; >75%, likely; >95%, very likely; >99% almost certain.