Validating Two Systems for Estimating Force and Power

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Key words
- force plate
- kinetic
- kinematic
- acceleration

Abstract

This study examined the validity of 2 kinematic systems for estimating force and power during squat jumps. 12 weight-trained males each performed single repetition squat jumps with a 20-kg, 40-kg, 60-kg and 80-kg load on a Kistler portable force plate. A commercial linear position transducer (Gymaware [GYM]) and accelerometer (Myotest® [MYO]) were attached to the bar to assess concentric peak force (PF) and peak power (PP). Across all loads tested, the GYM and MYO estimates of PF and PP were moderately to strongly correlated ($P \leq 0.05–0.001$) with the force plate measurements ($r = 0.59–0.87$ and $r = 0.66–0.97$), respectively. The mean PF and PP values were not significantly different between the 2 kinematic systems and the force plate, but the estimates did produce some systematic bias and relatively large random errors, especially with the 20-kg load (PF bias >170 N, PF error >335 N, PP bias >400 W, PP error >878 W). Some proportional bias was also identified. In summary, the estimation of PF and PP by a linear position transducer and accelerometer showed moderate to strong relative validity and equivalent absolute validity, but these estimates are limited by the presence of bias and large random errors.

Introduction

The accurate and reliable assessment of force and power are fundamental to sports testing, training and rehabilitation. Force can be described as the ability of muscle/s to produce tension, whereas power is the expression of force at a given velocity [7]. The direct acquisition of this kinetic data requires a force plate or platform, which is not always a practical and cost-effective option, and generally limited to lab-based assessments [8,22]. Thus, kinematic systems (e.g. linear position transducers, accelerometers) are becoming increasingly popular as tools for estimating the force and power outputs with exercise.

Linear transducers use a tethered cord (attached to a person or equipment) to extract time-displacement data and from this, movement velocities and subsequent accelerations are calculated. Through the process of differentiation, this kinematic data can be used to estimate forces and power when the mass of the load and/or subject moved are factored in [8,9]. Some commercially available linear transducers can also offer additional features such as real-time feedback, wireless transmission and/or online support services. Valid estimates of force and/or power ($r = 0.86–1.00$) have been reported during the performance of isoinertial exercise using a single linear transducer system [8,9].

Accelerometers can also be used to estimate force and power via the differentiation of acceleration and mass data [16,20]. Due to their small size, portability and ease of use, these devices can be attached to a wide range of equipment or even directly to a person during sporting and normal everyday activities, thereby offering greater versatility than linear transducers. Tri-axial accelerometers also have the potential for assessing human movement in 3 different planes, especially when coupled with other devices (e.g. gyroscope, magnetometer). The validity ($r = 0.85–0.99$) of accelerometers for calculating force, velocity and power during isoinertial exercise has been confirmed [4,16,20].

Despite their relative validity, the performance estimates from linear transducers or accelerometers can still differ from criterion values [5,6,15,16,20]. This highlights the need to address both the relative and absolute validity of

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a given measurement system. Little research has also described the criterion and concurrent validity of both instruments during a dynamic exercise relevant to sport (e.g. loaded squat jumps) and in a trained population. Finally, little research has additionally described the presence of bias within the estimated performance values. Addressing these issues would allow researchers and practitioners to make informed decisions about the use of each kinematic system in different constructs.

This study assessed the validity of 2 commercially available kinematic systems, a linear position transducer and accelerometer, for estimating peak force (PF) and peak power (PP) during squat jumps in weight-trained males. We hypothesized that each system would exhibit relative validity (i.e., strong correlations), but their absolute validity (i.e., mean values) would differ from a criterion force plate. We also addressed the presence of systematic and proportional bias in the performance estimates.

Methods

▼

Participants

12 healthy males were recruited with a mean (±SD) age, height and body mass of 28.8±6.8 years, 181.1±8.4 cm and 86.8±9.2 kg, respectively. The criteria for study inclusion were; a weight-training background, being able to squat 1.5 times their body mass and no injuries or conditions that would prevent them from safely undertaking the testing procedures. Each participant read and signed an informed consent form and filled out a health questionnaire. The Human Subject Ethics Committee of Swansea University provided ethical approval. This study was performed in accordance with the ethical standards of the International Journal of Sports Medicine [12].

Testing procedures

The testing procedures involved the simultaneous assessment of squat jump force and power using 2 kinematic (linear transducer, accelerometer) systems and a kinetic (force plate) system. Before testing, subjects performed a light warm-up comprising of dynamic bodyweight exercise and stretching. Next, 2× single repetition squats were performed with a 20-kg, 40-kg, 60-kg and 80-kg load (including the 20-kg bar mass) with 2 min rest separating each trial. The squats were performed using a standard technique [5,6]. Subjects began in a standing position, feet shoulder width apart, with the loaded bar placed on the shoulders and upper back. Subjects then slowly descended to a self-selected depth, keeping the head up and back straight, before extending upwards to the start position. Fast concentric movements were performed with subjects attempting to leave the ground with each lift. For safety reasons, subjects were instructed to extend up onto the toes when lifting the 80-kg load, but to maintain ground contact at all times.

Subjects performed their squats directly on top of a Kistler portable force plate (Type 92866AA, Kistler Instruments Ltd, Farnborough), which was used to collect ground reaction force (GRF) data. The force plate was positioned in the centre of the squat rack and stabilized using a solid wooden base that was also flush with the force plate surface. A commercial linear position transducer (Gymaware [GYM], Kinetic Performance Technology, Australia) was also tested, consisting of a linear encoder unit which relays information (via infrared signals) to a hand-held unit. The connection cable was attached to the right side of the bar with the encoder placed directly under, and perpendicular to, the bar movements. A light weight (<200 g) commercial tri-axial accelerometer (Myotest® [MYO] – Myotest Inc, Switzerland) was attached to the bar using a custom-built plastic clip. The device was placed near the centre of the bar, between the shoulder and thumb of the right hand, and kept vertical for each lifting movement. ○ **Fig. 1** shows the attachment for the 2 kinematic devices to the squatting bar.

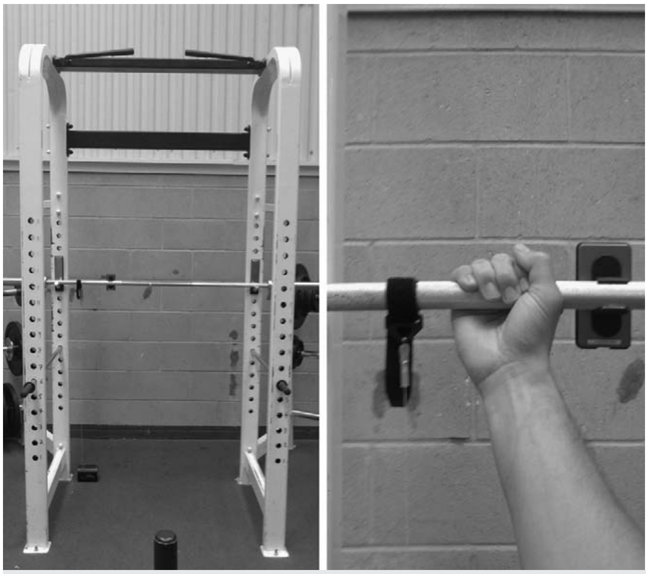

Fig. 1 Attachment of the 2 kinematic systems to the squatting bar.

Data analysis

Data from the force plate were sampled at a rate of 1 000 Hz for all jumps and the platform's calibration was confirmed pre and post testing. The vertical component of GRF, as each subject performed their squat jumps, was used in conjunction with their body weight to determine instantaneous velocity and displacement of the subject's centre of gravity (CG) [13]. Instantaneous power was determined as follows:

$$\text{Power (W)} = \text{vertical GRF (N)} \times \text{vertical velocity of CG (m.s}^{-1})$$

In order to determine the velocity of the subject's CG numerical integration was performed using Simpson's rule with intervals equal to the sample width. Prior to the calculation of the strip area, the subject's body weight was subtracted from the GRF values. The area of the strip then represented the impulse for that time interval. Using the relationship that impulse equals change in momentum; the strip area was divided by the subject's mass to determine the CG change in velocity, which was then added to the CG's previous velocity to produce a new velocity for that time interval. The CG velocity was taken to be zero prior to the initiation of the jump and specifically at the point identified as the start of the jump. This point was defined as the time when the subject's GRF exceeded the mean ± 5 standard deviations from the values obtained in the second (stationary body weight measuring) phase immediately prior to the command to jump [21]. The determination of power or velocity requires the force time history to be integrated and this has the effect of attenuating any noise present in the original signal [23], although this process is apparently sensitive to drift and the choice of integration constants [11]. In regards to the physical equipment, all screened cables and earth connections were checked for integrity, and the testing location was chosen to reduce potential sources of mechanical or electrical interference.

The GYM displacement data were time-stamped with a 1 millisecond resolution and then down-sampled to 50 Hz for analysis using a customized software programme. The sampled data were not filtered [9]. Instantaneous bar velocity was calculated for each time interval as bar displacement over change in time. Acceleration was determined from the change in velocity over the change in time for consecutive data points. Instantaneous force was then determined by multiplying system mass (i.e., external load and body mass) and acceleration, and instantaneous power by multiplying force and velocity, as follows:

Force (N) = system mass (kg) × vertical acceleration of the bar ($m.s^{-2}$) plus acceleration due to gravity ($m.s^{-2}$)

Power (W) = vertical force (N) × vertical bar velocity ($m.s^{-1}$)

The MYO data were down-sampled to 500 Hz and low-pass filtered (4th order, Butterworth) with a cut-off frequency of 10 Hz using a customized computer programme (Labview 8.0, National Instruments, USA). The acceleration data were multiplied by the combined mass of the external load and each subject to determine instantaneous forces, as follows:

Force (N) = (system mass [kg] × vertical acceleration of the bar [$m.s^{-2}$]) – (system mass [kg] × acceleration due to gravity [$m.s^{-2}$])

Acceleration data were multiplied by the time interval between data points to yield instantaneous velocity and instantaneous power was calculated as described above. Pilot testing in trained males revealed reliable estimates of force (coefficients of variation = 2.5 % and 2.6 %) and power (3.0 % and 3.3 %) from the GYM and MYO systems, respectively.

Statistical analyses

Concentric PF and PP for each load were the main outcome variables. The relative validity of each kinematic system was assessed using least squares linear regression [18]. Absolute validity was assessed using repeated measures analysis of variance and Tukey post hoc comparisons, where appropriate. Bland-Altman plots were used to detect the presence of systematic bias ± random error, after plotting the mean of 2 systems against the system differences [1,3]. Paired t-tests were used to detect any systematic bias between the system means. Proportional bias was assessed by linear regression comparisons between the system means and differences. The criterion level for significance was set at $P \leq 0.05$.

Results

Across all 4 loads, the estimates of PF and PP from the 2 kinematic systems were not significantly different from the measured force plate data (▶ **Fig. 2, 3**). As seen in ▶ **Table 1**, the PF values from the GYM and MYO systems were significantly correlated ($P \leq 0.05$–0.001) with corresponding force plate measurements ($r = 0.59$–0.87 and $r = 0.87$–0.97, respectively). The GYM and MYO estimates of PP were also significantly correlated to the force plate data ($r = 0.62$–0.82 and $r = 0.66$–0.90, respectively) (▶ **Table 2**).

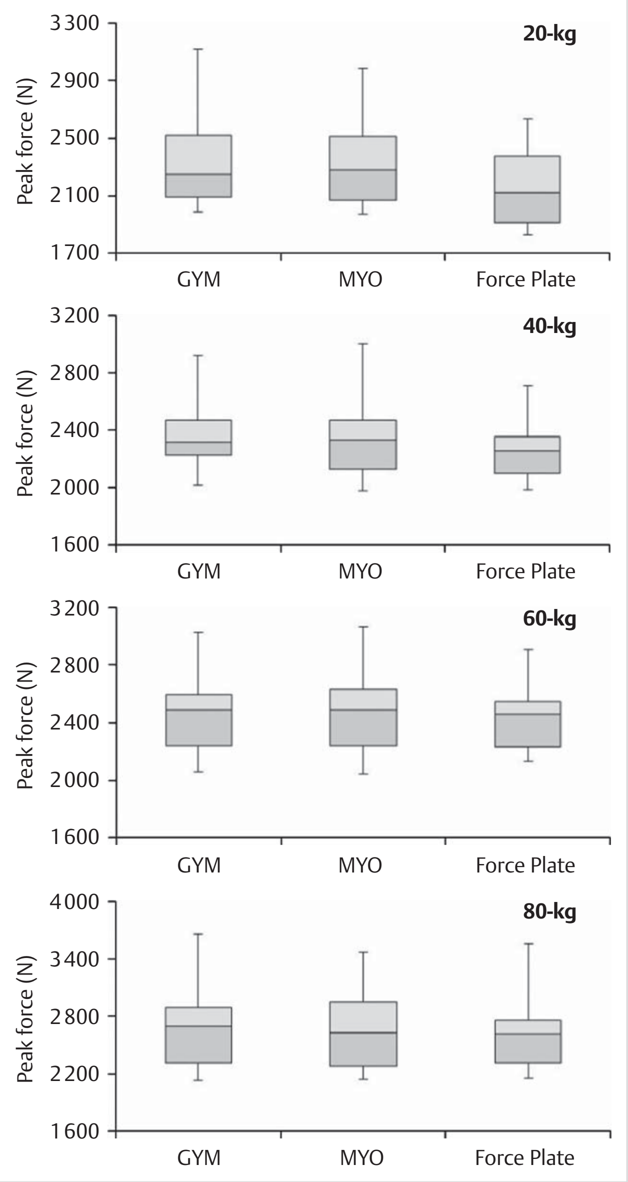

Fig. 2 Peak force values from the Gymaware (GYM), Myotest (MYO) and force plate systems. The boxed data represent the median values with the 25th percentile and 75th percentiles, with the lower and upper error bars indicating the minimum and maximum values, respectively.

Bland-Altman plots revealed systematic bias between GYM PF (20-kg and 40-kg loads) and PP (20-kg load) when compared to the force plate data ($P < 0.05$). Similar bias was observed for the MYO assessment of PF with the 20-kg load ($P < 0.05$). For both kinematic systems, the random errors in PF and PP were greatest with the 20-kg load and decreased across the heavier loads tested. Based on the correlational evidence, varying degrees of proportional bias were also noted ($r = 0.07$–0.62), but only the MYO estimate of PF (60-kg) reached statistical significance ($r = 0.62$, $P < 0.05$), as seen in ▶ **Fig. 4**.

Discussion

The PF and PP estimates from the GYM and MYO systems were moderately to strongly correlated with the corresponding force plate data across each load. These results are supported by pre-

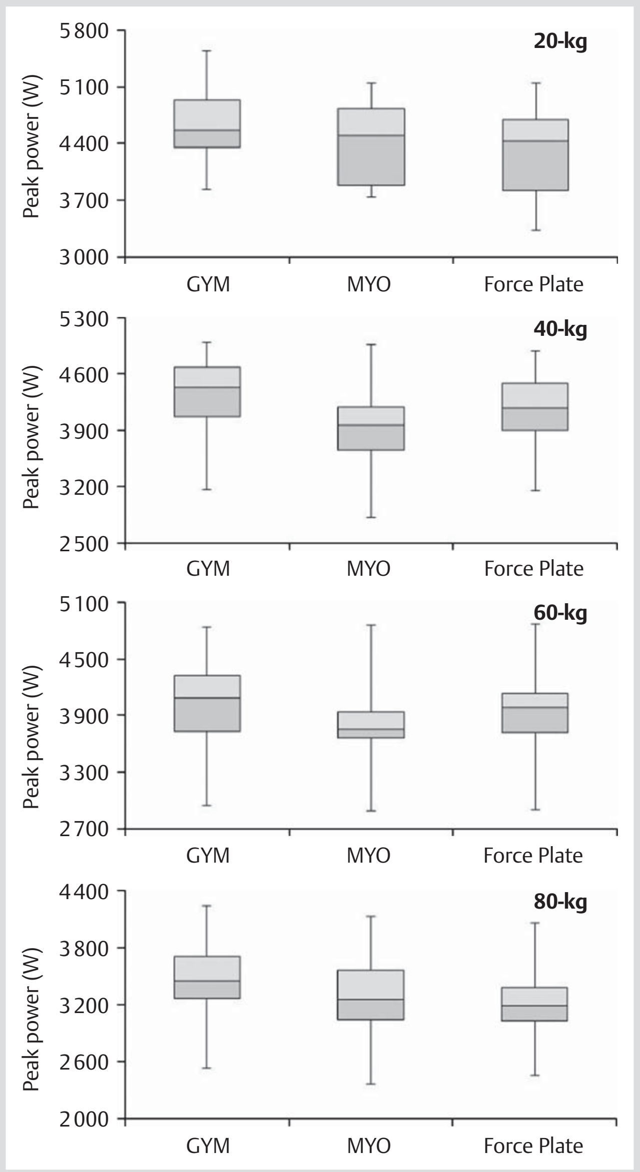

Fig. 3 Peak power values from the Gymaware (GYM), Myotest (MYO) and force plate systems. The boxed data represent the median values with the 25th percentile and 75th percentiles, with the lower and upper error bars indicating the minimum and maximum values, respectively.

Table 1 Peak force (PF) results vs. the force plate data.

	20-kg	**40-kg**	**60-kg**	**80-kg**
GYM				
correlations	0.59*	0.83**	0.87**	0.87**
systematic bias (N)	+202$^{\sigma}$	+108$^{\sigma}$	+39	+57
random error (N)	±579	±255	±255	±414
proportional bias	0.29	0.19	0.29	0.13
MYO				
correlations	0.87**	0.89**	0.95**	0.97**
systematic bias (N)	+171$^{\sigma}$	+73	+32	+7
random error (N)	±336	±256	±196	±219
proportional bias	0.41	0.51	0.62*	0.21

GYM = Gymaware; MYO = Myotest

* Significant *r*-values $P<0.05$, ** Significant *r*-values $P\leq 0.001$

$^{\sigma}$Significant difference between the system means $P<0.05$

vious research [8,9,16,20] to confirm our initial hypothesis of strong relative validity for each kinematic system. Specifically, they each provide valid calculations of the individual variances in PF and PP during isoinertial exercises (e.g. squats, squat jumps, countermovement jumps, bench presses, bench throws). Furthermore, it appears that these estimates are valid across a wide range of loading conditions up to 90% 1RM. Since most studies have only examined movements performed in a vertical plane, it would now be informative to address the validity of each kinematic system during exercise performed in a horizontal or multiple planes (e.g. sprint starts, bounding, broad jumps).

The mean PF and PP values from the kinematic systems were found to be equivalent to the force plate system. However, further examination revealed systematic bias and relatively large random errors in the estimated values, especially with the 20-kg load (PF bias >170 N, PF error >335 N, PP bias >400 W, PP error >878 W). Other research have also identified different force and/or power values (v. criterion data) derived from accelerometers [16,20] and a single linear position transducer [5,6,15]. One likely reason lies in movement disparities between the centre of mass (measured by the force plate) and bar movement (measured by the kinematic systems) during the squat jumps, particularly when lighter loads are moved. Indeed, methods that rely solely on kinematic data cannot account for body movement that occurs independently of the bar [6]. Bar movements in the horizontal plane could provide another source of error, especially during free-weight exercises. Further problems lie in the differentiation of accelerations and velocities which can magnify any errors in data acquisition [23] and subsequent curve estimations, along with the varied sampling frequencies for each device in this study (50 Hz, 500 Hz and 1 000 Hz).

The exercise tested in this study requires some consideration. Experimental studies have demonstrated that different testing methods, involving one or more kinematic and/or kinetic systems, can strongly influence the force and power outputs obtained during squat jumps [5,6,15,17]. A review of these methods and calculations has highlighted several problems when assessing this exercise [10]. For example, assumptions that the human body works as a single rigid system and that the bar velocity is equivalent to that of the entire system [10]. It is also assumed that acceleration occurs uniformly between exercises and individuals. The need to exclude the mass of the shanks and feet, due to their static positioning prior to the jump squat takeoff, the effects of free-weight exercises and instructions given to participants are other considerations [10]. Given these issues, the best method/s for characterizing squat jump performance has yet to be defined.

Although only the MYO estimate of PF exhibited significant proportional bias (i.e., heteroscedastic error), some of the non-significant results also tended to suggest the presence of heteroscedasticity, based on the criteria of $R^2>0.1$ [2]. These results are not uncommon for the measurement of variables in sports medicine and sports science [19]. The issue of proportional bias can be partly resolved by the log transformation of data [3], as we found (data not shown). It is important to note that measurement bias can also be detected using linear regression models [14,18], but their discussion is beyond the scope of this paper. Irrespective of the statistical method used, one must still decide on acceptable levels of bias associated with a given instrument and the subsequent applications in sport. Taken together with other information (e.g. size, portability, ease of use, cost effectiveness), these results can assist researchers and practitioners in making informed decisions about the use of each kinematic system within a specific construct.

Table 2 Peak power (PP) results vs. the force plate data.

	20-kg	40-kg	60-kg	80-kg
GYM				
correlations	0.67*	0.82**	0.74*	0.62*
systematic bias (W)	+401σ	+178	+45	+198
random error (W)	±879	±611	±748	±762
proportional bias	0.08	0.10	0.04	0.07
MYO				
correlations	0.66*	0.88**	0.82**	0.90**
systematic bias (W)	+141	−180	−112	+23
random error (W)	±896	±593	±610	±400
proportional bias	0.08	0.46	0.07	0.19

GYM = Gymaware; MYO = Myotest

* Significant *r*-values *P*<0.05–0.01, σ Significant *r*-values *P*≤0.001

σ Significant difference between the system means *P*<0.05

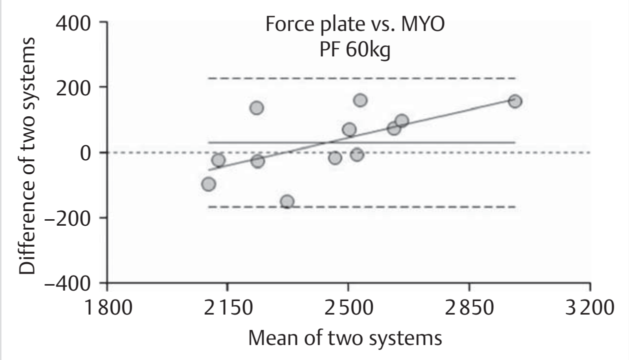

Fig. 4 Plot of the Myotest (MYO) and force plate system means against the system differences in peak force (PF). The mean values and upper and lower 95 % confidence intervals are presented, along with the regression line for the plotted data.

One of the study limitations is the small number of subjects assessed (n = 12), which can influence the interpretation of Bland-Altman plots [1] and the statistical power of our findings. Given the limited number of data points, it was also difficult to assess the uniformity (or lack thereof) of the random error across each of the measured variables. A review of gas analysis systems proposed that 40 subjects are needed for validation purposes [1], which could serve as a good starting point for research in this area. As a delimitation, the current study focused on the kinetic responses of the propulsive (i. e., lifting the load) phase of the squat jumps, not the deceleration (i. e., lowering the load) phase, and the population tested were weight-trained males.

In conclusion, the estimation of squat jump PF and PP (in the concentric phase) by a commercial linear position transducer and accelerometer both showed moderate to strong relative validity and equivalent absolute validity. However, the PF and PP estimates from the 2 kinematic systems are limited by the presence of systematic and proportional bias, along with relatively large random errors, which can affect their use within sport.

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