Development of a field test to estimate peak vertical mechanical power of elite male rugby union players.

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Development of a field test to estimate peak vertical mechanical power of elite male rugby union players

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Abstract

Rugby union is an intermittent high intensity sport that requires players to demonstrate aerobic endurance, strength and power. Whereas the assessment of aerobic endurance and strength are well established, the assessment of rugby-specific muscle power is less well developed. A force platform can be used to accurately measure mechanical power, produced by the legs, in a countermovement jump. However this is not a practical option for a field test. Consequently, a number of attempts have been made to predict leg power from the height jumped by a subject in a countermovement jump. The purpose of the present study was to investigate the validity of field tests, which predict leg power, based on the height jumped in a countermovement jump in elite rugby players. However, due to a lack of clarity with regard to methodology all existing prediction equations have questionable validity. There are a number of reasons for the lack of clarity, but one common reason is the absence of a well defined criterion method for measuring instantaneous vertical mechanical power of the whole body centre of gravity of a countermovement jump, using a force platform. Consequently it was necessary to develop and define a criterion method to measure instantaneous vertical mechanical power of the whole body centre of gravity of a countermovement jump, using a force platform. The criterion method specifies a sampling frequency of 1000Hz, Simpson's rule for integration of the force record and body weight measurement and start time criterion based on force records during quiet standing prior to jumping. Once the criterion method had been defined, it was used to measure peak instantaneous mechanical power of the whole body centre of gravity of 59 elite under 21 year old male, rugby union players. Body mass and jump height were used as predictor variables and regression equations were developed to predict absolute and relative peak vertical mechanical power output. The regression equation developed using multiple regression was:
peak estimated $power_1$ (W) =

$$[9026.19 \times \text{jump height (m)}] + [48.96 \times \text{body mass (kg)}] - 2910.9$$

($R^2 = 0.681$, $p < 0.001$, S.E.E. = 412 W).

The regression equation developed using linear regression was:
peak estimated $power_2$ (W) =

$$[\text{body weight(N)}] \times [10.187 \times \text{jump height (m)} + 1.704]$$

($R^2 = 0.713$, $p < 0.001$, S.E.E. = 388 W).

The linear regression produced less error, an improvement of 5% over the multiple regression equation. The linear regression equation should be used in place of existing regression equations when estimating peak power in elite rugby players. Further studies should investigate then equations' ability to detect change in power after training intervention and their validity for use with different populations.

Declaration

I hereby declare that this thesis has been composed by myself, that the work is the result of my own investigations except where assistance has otherwise been acknowledged, that the work has not been previously submitted in candidature for any other degree, that all sources of information have been specifically acknowledged by means of reference, and that consent is provided for the thesis to be made available for photocopying and for inter-library loan.

Signature . . . . Date . . . 20/3/08 . . .

N.J.Owen

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Pp_{est2} = peak power estimated from jump height using relative peak power, S_{ft} = jump height estimate determined from flight time, BW = body weight of subject.

Table 4.4 Comparison table of statistical variable for the absolute and relative regression equations

Chapter 1

Introduction

1.1 Physical fitness requirement for rugby

1.2 Assessment of muscular performance in rugby

1.3 Measurement of leg power based on performance in a countermovement jump

1.4 Objectives of the current study

1.1 Physical fitness requirements for rugby

Rugby union (rugby) is a popular contact sport worldwide with attendance figures at major internationals and championships of 40,000 to 70,000 per match (Maud and Schultz 1984; Douge 1988). A rugby game is played in two halves each lasting 40 minutes. The clock is normally stopped for the treatment of injuries, but otherwise time, made up of playing time and the time between stoppages and restarts, is continuous. Playing time ranges from 25 to 29 minutes per match (Morton 1978; McLean 1992; Menchinelli 1992). A rugby team has 15 players made up of 8 forwards who are primarily ball winners and 7 backs who are primarily ball carriers. In terms of physical fitness requirements, rugby is an intermittent high-intensity sport that requires the players, both forwards and backs to demonstrate high levels of aerobic endurance (jogging and running), strength and power (sprinting, jumping, mauling, scrummaging) throughout a game (Nicholas 1997).

1.2 Assessment of muscular performance in rugby

Whereas the general physical fitness requirements of rugby are well known, methods of assessing rugby-specific attributes of muscle function for the purpose of customising training are less-well developed. It is generally acknowledged that muscle power in the arms, trunk and legs is an important physical fitness attribute for performance in rugby (Nicholas 1997). Consequently muscle power should be an essential element in the regular assessment of muscle function in the training of rugby players (Cronin and Hansen 2005). Newton and Dugan (2002), who use the term 'strength diagnosis' in reference to the attributes of muscle function, suggest that the countermovement vertical jump is a useful measure of leg power in sports, like rugby, that involve repetitive explosive vertical jumping. Indeed, performance in vertical jumping, in various forms, has long been used as a test of leg power (Fox and Mathews 1972; Morton 1978; Harman et al. 1991; McLean 1992; Johnson and Bahamonde 1996; Sayers et al. 1999; Newton and Dugan 2002; Canavan and Vescovi 2004).

1.3 Measurements of leg power based on performance in a countermovement vertical jump

In the criterion (or reference) method of measuring leg power based on performance in a vertical jump, the subject is required to jump off a force platform. The vertical component of the ground reaction force is recorded from the start of movement to take-off. The force-time record is then integrated to produce the corresponding velocity-time data. Instantaneous power (P) is then calculated from the product of the force (F) and velocity (v) at the sampling frequency of the force platform: $P = F.v$ (Winter 2005). Figure 1.1, shows typical graphs of the vertical component of the ground reaction force against time for a countermovement jump together with the corresponding velocity-time and power-time graphs of the movement of the whole body centre of gravity (CG) of the subject.

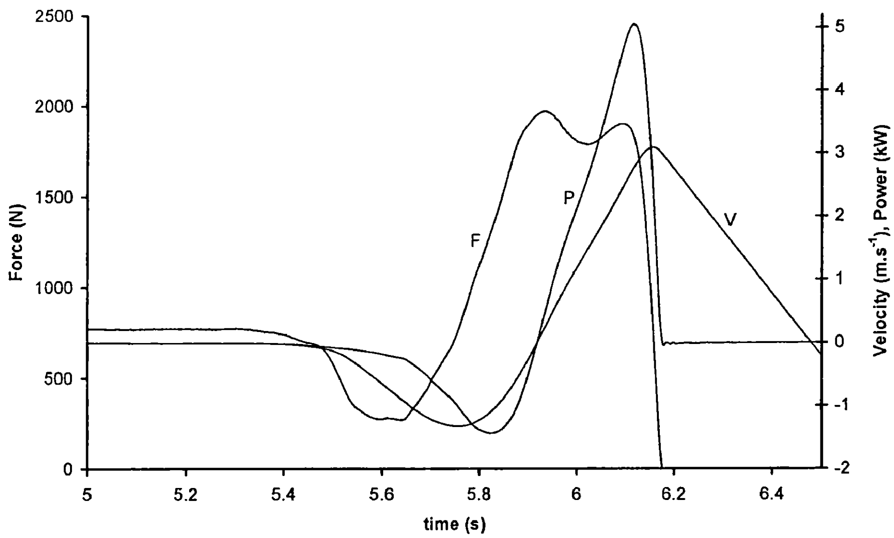


Figure 1.1: Typical vertical ground reaction force- time curve (F) and corresponding velocity-time (v) and power-time (P) curves for a countermovement jump

Whereas this method is valid (it measures the mechanical power of the leg extensor muscles) and well justified as a reference method (Hatze 1998), it is not very practical for field-testing as a force platform is not usually available in field settings. For this reason, a number of attempts have been made to devise field tests to predict leg power. The relationship between leg power (the rate at which the leg muscles do mechanical work in propelling the body upwards during the propulsion phase of the jump) and the effect of the work done (in terms of take-off velocity and height jumped) are shown in Figure 1.2.

Body mass is easy to measure and height jumped is relatively easy to measure in a field context. Not surprisingly, these variables have been the basis of a number

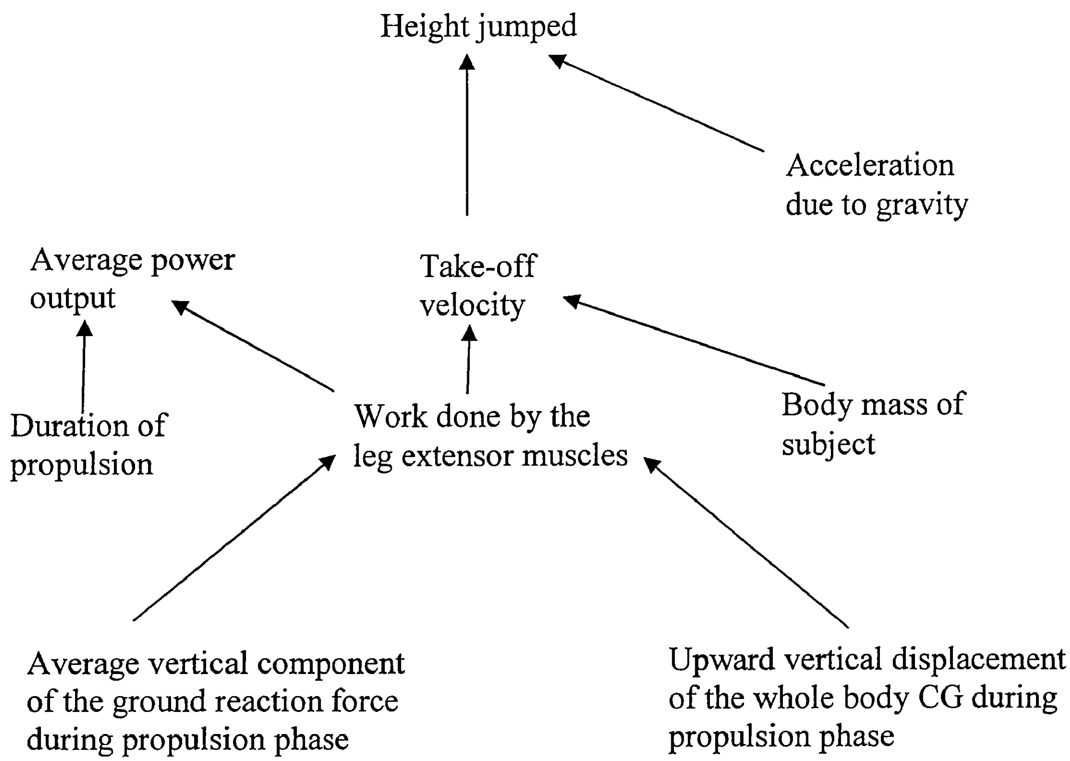


Figure 1.2: Relationship between average leg power and height jumped in a countermovement jump

of attempts to predict leg power. These include the Lewis formula (Fox and Mathews, 1974), the Harman formula (Harman et al. 1991) and the Sayers formula (Sayers et al. 1999). In addition to body mass and height jumped Johnson and Bahamonde (1996) also included subject height in their leg power prediction equation. As described in chapter 2, the validity of these formulae (regression equations) is not clear due to lack of clarity in the description of methods.

1.4 Objectives of current study

In light of the questionable validity of all the regression equations considered in chapter 2, the aim of the present study was to develop a field test to estimate peak vertical mechanical power output of the human body in a countermovement vertical jump for use with elite, under 21 year old male, rugby union players.

The objectives of the study were:

1. To establish a standardised criterion method of determining instantaneous vertical mechanical power output in a countermovement jump, utilising a force platform.
2. To determine peak vertical mechanical power output of a group of elite rugby players using the standardised criterion method.
3. To develop a regression equation, suitable for field use, to estimate peak vertical mechanical power output of the human body in a countermovement jump.

Chapter 2

Review of literature

2.1 Introduction

Countermovement jumps have been used for many years for the assessment of leg power and can be performed with a number of variations. Traditionally the most common form has been the Sargent jump, or jump and reach test (Sargent 1924). In this test, the subject, with finger tips of the preferred hand dusted with powdered chalk, performs a static reach to mark a wall or vertical board as high as possible whilst standing on tip toes. The subject then performs a countermovement jump in order to make a second mark on the wall or board as high as possible above the static reach mark. The vertical distance between the two marks, i.e. the height jumped, is recorded as an indirect measure of the subject's leg power. A recent variant of the jump and reach test utilises plastic markers, mounted on a vertical stand, that are caused to rotate when tapped by the subject to indicate the static reach height and jump height (Vertec jump trainer). Another variant estimates jump height from flight time. In this test, the subject performs a maximal effort jump for height from an instrumented mat, which records the time between take-off and landing (Carlock et al. 2004).

2.2 Kinematics of the vertical movement of the whole body centre of gravity in a countermovement jump

All variants of the countermovement jump have certain elements in common. A subject starts the movement standing in an upright position. The jump is then initiated by coordinated flexion at the ankles, knees and hips causing the whole body CG to move downwards: the countermovement. This phase involves eccentric action of the hip, knee and ankle extensor muscle-tendon units.

Following on from this phase, and in a single continuous movement, the direction of motion is changed and the subject commences the propulsive phase of the jump. In the propulsive phase the subject explodes upwards, by coordinated extension of the ankles, knees and hips, in an attempt to jump as high as possible. This phase of the jump involves concentric action of the hip, knee and ankle extensor muscle-tendon units. Figure 2.1 shows a sequence of key positions for a generic countermovement jump and the corresponding velocity-time and displacement-time histories. If the upward direction is taken to be positive then in the eccentric phase of the jump (A-B) the jumper's CG has negative displacement and consequently negative velocity and in the concentric phase (B-D) and upward flight phase (D-E) the CG has positive displacement and positive velocity with the velocity reaching a maximum value just before take-off. At the transition between the eccentric and concentric phase (point B) and at maximum height (point E) the vertical velocity of the CG is momentarily zero. After take-off the subject's CG continues with positive velocity until it has reached maximum height (E). After this point the subject falls back to the ground.

2.3 Kinetics of the vertical motion of the whole body centre of gravity in a countermovement jump

The changes in a subject's velocity and consequent displacement are brought about by forces acting on the subject due to gravity and coordinated muscle activity. When the subject is stationary, just before the initiation of the jump, the resultant force, R, acting on the subject must be zero. At this point the

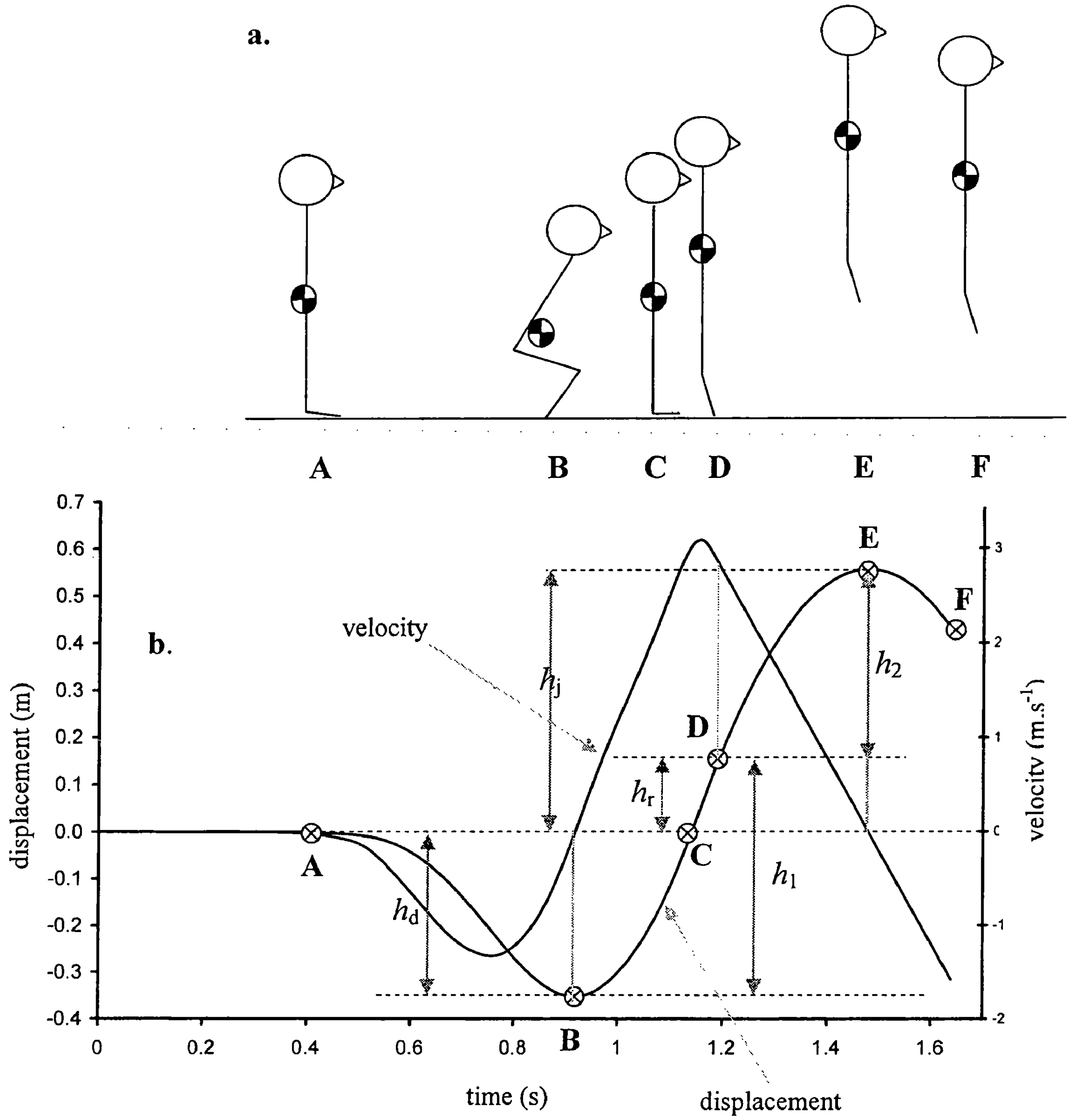


Figure 2.1: (a) Stick figure sequence and (b) corresponding displacement-time and velocity-time histories of the vertical movement of the whole body CG in a typical countermovement jump.

A = start of jump and eccentric phase
B = limit of downward motion and end of eccentric phase of jump and start of the concentric phase; velocity is zero
C = position in jump where subject's CG is at the same vertical displacement as at the start of the jump
D = instant of take-off and end of concentric phase NB just after peak velocity
E = maximum height achieved by subject's CG; velocity is zero
F = arbitrary point after max height
h_d = depth of countermovement
h_j = jump height, height gained by CG above starting height
h_r = reach height, the height at take-off relative to the starting position.
h_1 = displacement of CG during propulsive phase = $h_d + h_r$
h_2 = flight height, height gained by CG after take-off = h_j - h_r

vertical ground reaction force, F, acting on the subject is equal and opposite to the subject's weight, W, i.e. R = W-F = 0. Any reduction in F would result in a resultant downward force acting on the subject and, consequently, downward acceleration of the CG, i.e. W > F. The resulting negative impulse would result in downward velocity of the CG. If F > W, there would be a resultant upward force acting on the subject and, consequently, downward deceleration or upward acceleration of the CG, resulting, respectively in a decrease in downward velocity or an increase in upward velocity of the CG. Figure 2.2 shows how the impulse of the resultant force relates to the ground reaction force acting on a subject performing a countermovement jump. The initial negative impulse (the first unweighting phase) applied to the subject produces downward velocity of the subject's CG. Before the subject can start to move upward, the downward velocity of the CG must be reduced to zero, i.e. there needs to be an equal, but opposite, impulse; this is the first part of the positive impulse (first weighting phase). The remaining positive impulse (second weighting phase) generates upward velocity of the subject's CG. Maximum upward velocity of the CG is achieved just before take-off, i.e. between positions C and D in Figure 2.2, just prior to the second unweighting phase. When the subject is no longer able to maintain a ground reaction force greater than their body weight, just prior to take-off, there is a small negative impulse (second unweighting phase) and, consequently, a small decrease in the vertical velocity. When the subject is airborne the only force acting is W (due to the relatively low velocity of the CG, air resistance is assumed to be negligible) and the trajectory of the CG is the same as a projectile in the absence of air resistance. Consequently, the trajectory of the

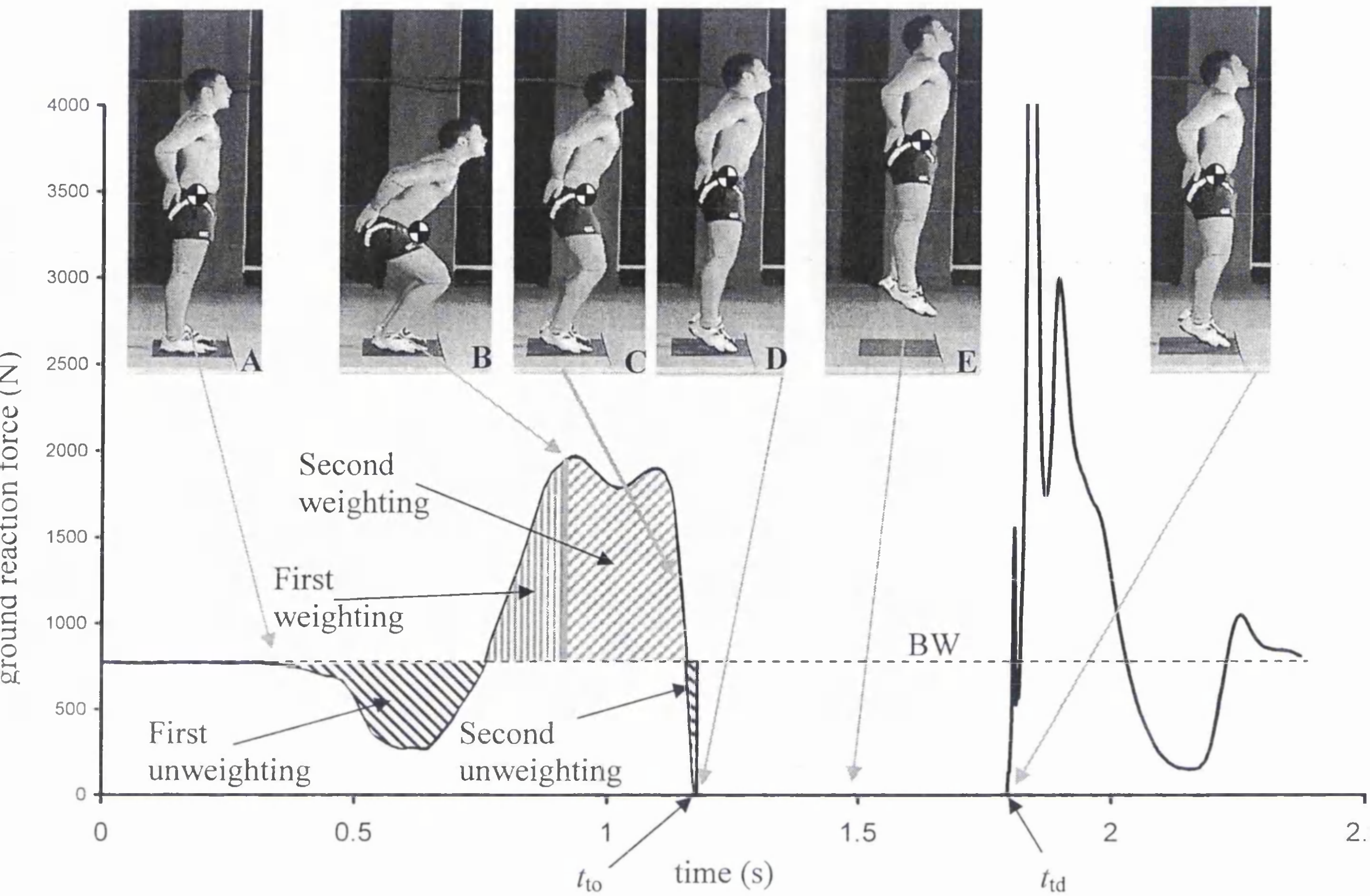


Figure 2.2: Typical vertical ground reaction force-time curve for a countermovement jump showing the relationship between the impulse of the vertical resultant force (represented by the shaded areas), the ground reaction force and the corresponding position of the subject. Positions A.B,C,D and E correspond to Figure 2.1, t_{to} = time at take-off, t_{td} = time at landing

Negative impulse =

Positive impulse = and

BW = body weight

CG can be determined by applying the equations of uniformly accelerated motion. The time between the instant of take-off (t_{to}) and that of landing (t_{td}) is termed the flight time (t_f). Figure 2.3 illustrates the relationship between the vertical ground reaction force acting on the subject and the corresponding velocity and displacement of the subject's CG.

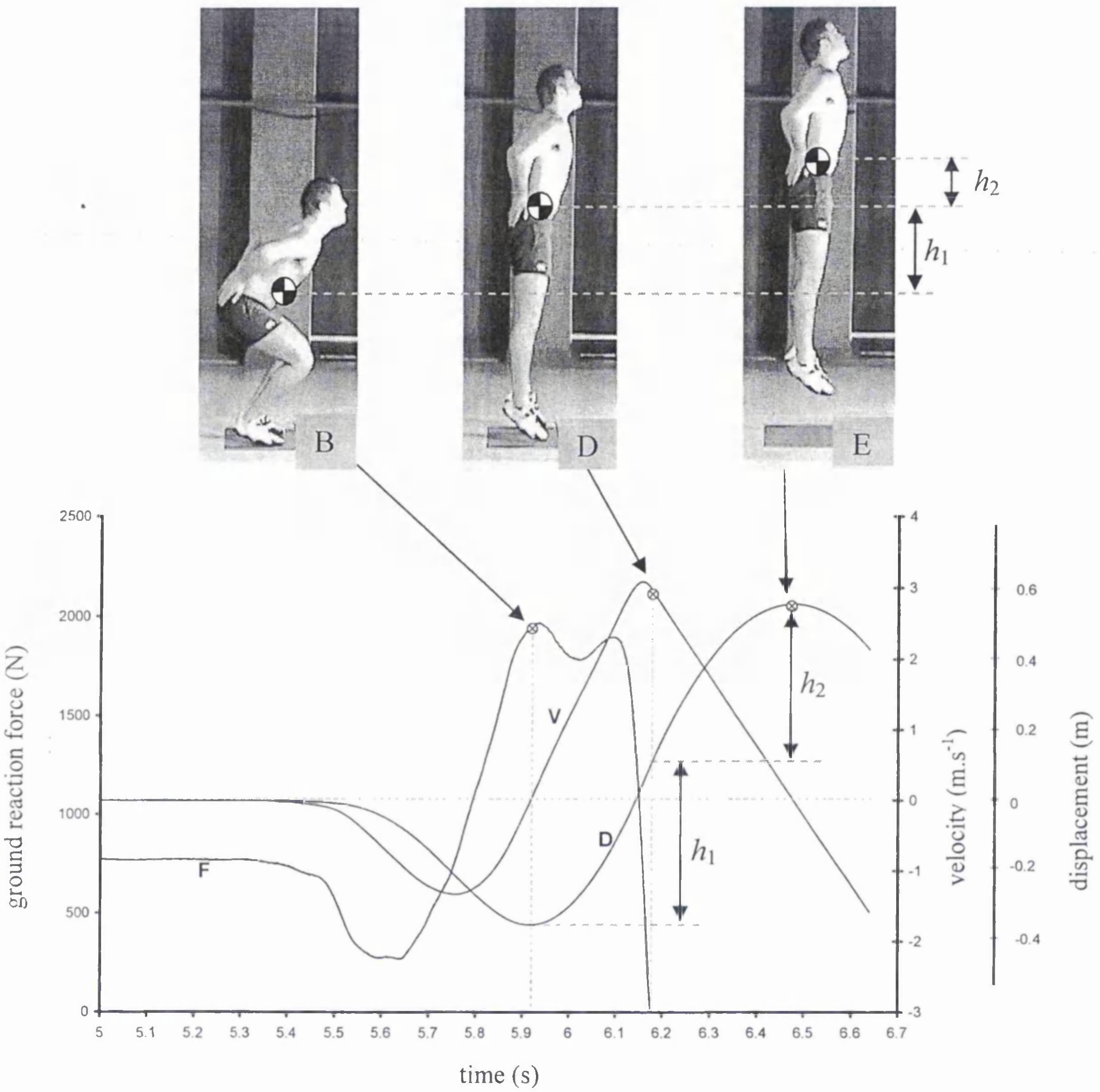


Figure 2.3: Typical vertical ground reaction force-time curve (F) and corresponding velocity-time (V) and displacement-time (D) curves for a countermovement jump.
h_1 = displacement of CG during propulsion phase, h_2 = height gained by CG after take-off. Positions B, D and E correspond to Figures 2.1 and 2.2

2.4 Measurement of vertical ground reaction force using a force platform

In the study of human movement a force platform is a device that measures ground reaction force-time histories in three orthogonal dimensions (vertical and two horizontal). Force platforms tend to be square or rectangular with force transducers mounted in each corner. A force transducer is a device that converts a force applied to the force platform into some other physical quantity which in turn is converted into a voltage signal proportional to the applied force. Figure 2.4 shows a force platform with a glass top plate that allows the force transducers in each corner to be seen clearly. The force platform is constructed in such a way that any force applied to it is transmitted to the ground through the transducers. Each of the four force transducers actually consists of three individual transducers, one for each of the orthogonal directions. This discussion will

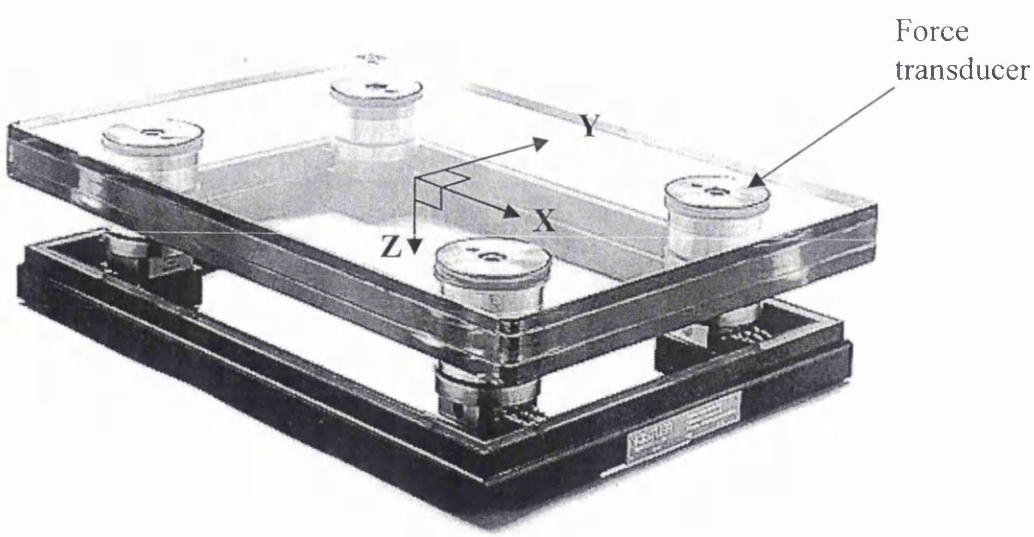


Figure 2.4 A glass topped force platform showing the four force transducers and the convention for applied force direction (courtesy of Kistler UK). Conventions for force direction differ between manufacturers.

only consider the vertical, Z, direction; however the principles for the other directions are the same.

Force transducers used in the construction of force platforms are one of three types:

Piezoelectric: piezoelectric transducers are quartz crystals that convert an applied force into an electrical charge that is proportional to the applied force.

Strain gauge: a strain gauge consists of a thin ribbon of metal which has a characteristic electrical resistance. When the metal ribbon is deformed, by an applied force, its electrical resistance changes in proportion to the applied force

Hall effect sensors: a hall effect sensor is a semiconductor device that is sensitive to magnetic fields. If a magnet were placed on a mechanical spring such that an applied force would alter its proximity to a hall effect sensor, then as the applied force changed a proportional change in the conductance of the hall effect sensor would result.

The materials, characteristic physical quantities, effect of applied force and units specific to each type of transducer are listed in Table 2.1. Force transducers do not produce signals that are directly compatible with a digital computer and, as such, additional signal conditioning equipment is necessary in order to achieve an appropriate interface. Each of the characteristic quantities produced by a transducer is first converted into a voltage, proportional to the original signal. The voltage signal is then converted into a digital signal, via an analogue to digital (A to D) converter. Once the signal is in digital form it can be processed, displayed

Transducer type	Transducer material	Mechanical effect of applied force	Electrical change due to applied force (output variable)	Units (symbol)
Piezoelectric	Quartz crystal	Compression or tension	Charge	Coulomb (C)
Strain gauge	Metal alloy	Deformation, bending	Resistance	Ohm (Ω)
Hall effect	Semiconductor	Change in proximity of a magnet to transducer	Conductance	Siemens (S or Ω^{-1})

Table 2.1: Different types of force transducers: the materials they are constructed from, the mechanical effects of an applied force and the consequent changes in the transducers' electrical characteristics.

and recorded, using specialised software, by a computer. A functional diagram of the components necessary for a single vertical force transducer to be connected to a data logging computer are shown in Figure 2.5. In a force platform there would be four vertical transducers (one at each corner of the platform) and the total vertical force would simply be the arithmetic sum of the output of the individual transducers. The summing would be carried out within the computer as all transducer signals are usually input into the computer individually.

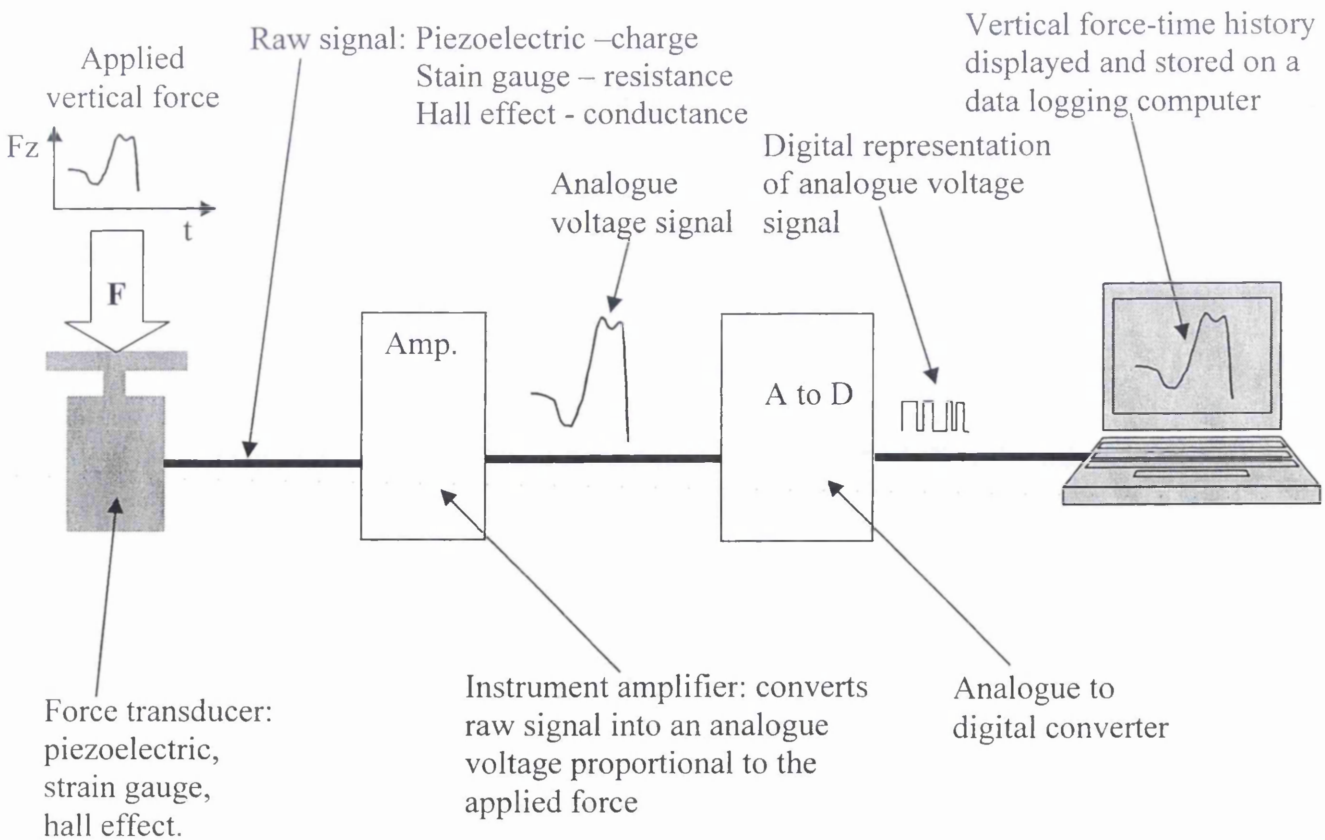
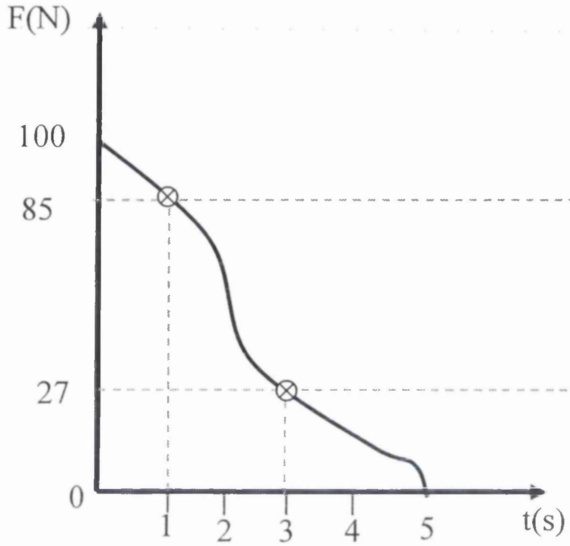


Figure 2.5: A single channel vertical force transducer system showing the components necessary to collect a force-time history on a digital computer.

2.4.1 Resolution of a force platform

Force platforms have a very large dynamic range, from less than 10 newtons to many thousands of newtons. However there are limitations within the analogue to digital converters which restrict the resolution of the system. Analogue signals, signals that can vary infinitely, are represented digitally as a series of discrete values; that is they can only take certain values. The resolution of a digital signal depends on the number of discrete values that are available to represent the corresponding analogue signal. A digital signal is made up of a series of 0's and 1's, or bits, that form a binary number; the number of discrete levels that can be represented by the binary number is dependent on the length of the binary number i.e. the number of bits. A simplified example of an analogue signal being represented by binary numbers that are 2 and 3 bits long is given in Figure 2.6. A 2 bit binary number can represent 4 discrete values (2^2), a 3 bit binary number can represent 8 discrete values (2^3). If a 2 bit binary number was representing a



Binary numbers and the forces they represent for a range of 0 -100 N

2 bit		3 bit	
num.	F (N)	num.	F (N)
11	100	111	100
		110	86
10	67	101	71
		100	57
01	33	011	43
		010	29
00	0	001	14
		000	0

Figure 2.6 A simplified example of an analogue force-time history and corresponding force values as represented by 2 and 3 bit binary numbers.

0 to100 N scale then only 4 different values could be represented. The interval between these values is given by the full scale value, 100 N, divided by 3, giving an interval, or resolution, of 33 N (0 d.p.'s). A 2 bit digital representation of 100 N would only then give 4 discrete values namely 0, 33, 67 and 100 N. In Figure 2.6, a force value of 27 N would have a value of 33 N if represented by a 2 bit digital number and a value of 29 N if represented by a 3 bit digital number. A force value of 85 N would have a value of 100 N if represented by a 2 bit digital number and a value of 86 N if represented by a 3 bit digital number. If the number of bits representing an analogue signal increase then so does the resolution, however if the range of the signal increases then the resolution decreases. Modern

force platforms have analogue to digital converter that are usually either 12 bit giving 4096 discrete levels (2^{12}) or 16 bit giving 65,536 discrete levels (2^{16}). The resolution of a system would depend on the range of force being measured. A range of 10 kN would yield a resolution of 2.4 N for 12 bit (i.e. 10,000 ÷ 4095 [2^{12}-1]) and 0.2 N for 16 bit. If a positive and negative scale was being used (± 10 kN) then resolution would be halved.

Force platforms will normally have a number of ranges such that lower ranges, for example ±1 kN range would have a higher resolution than a ±10 kN range but it would be limited to measuring a 1 kN maximum force. Lower ranges would typically be used for balance and gait measurements whereas higher ranges would typically be used for impact and jumping measurements.

2.4.2 Sampling rate of a force platform

A force platform system records a force-time history. It can only represent force by discrete values; the same is also true for time, it can not be represented continuously. Therefore a force platform system can only measure force values at certain (regular) time intervals, not continuously. The number of times that force values are measured every second is termed the sample rate or sample frequency and is measured in the S.I. unit hertz (Hz,[s^{-1}]). The sample rate of most force platforms can be pre-selected, usually from 20 Hz to 2 kHz. In between sample points no information is known; it is therefore important to choose a sample

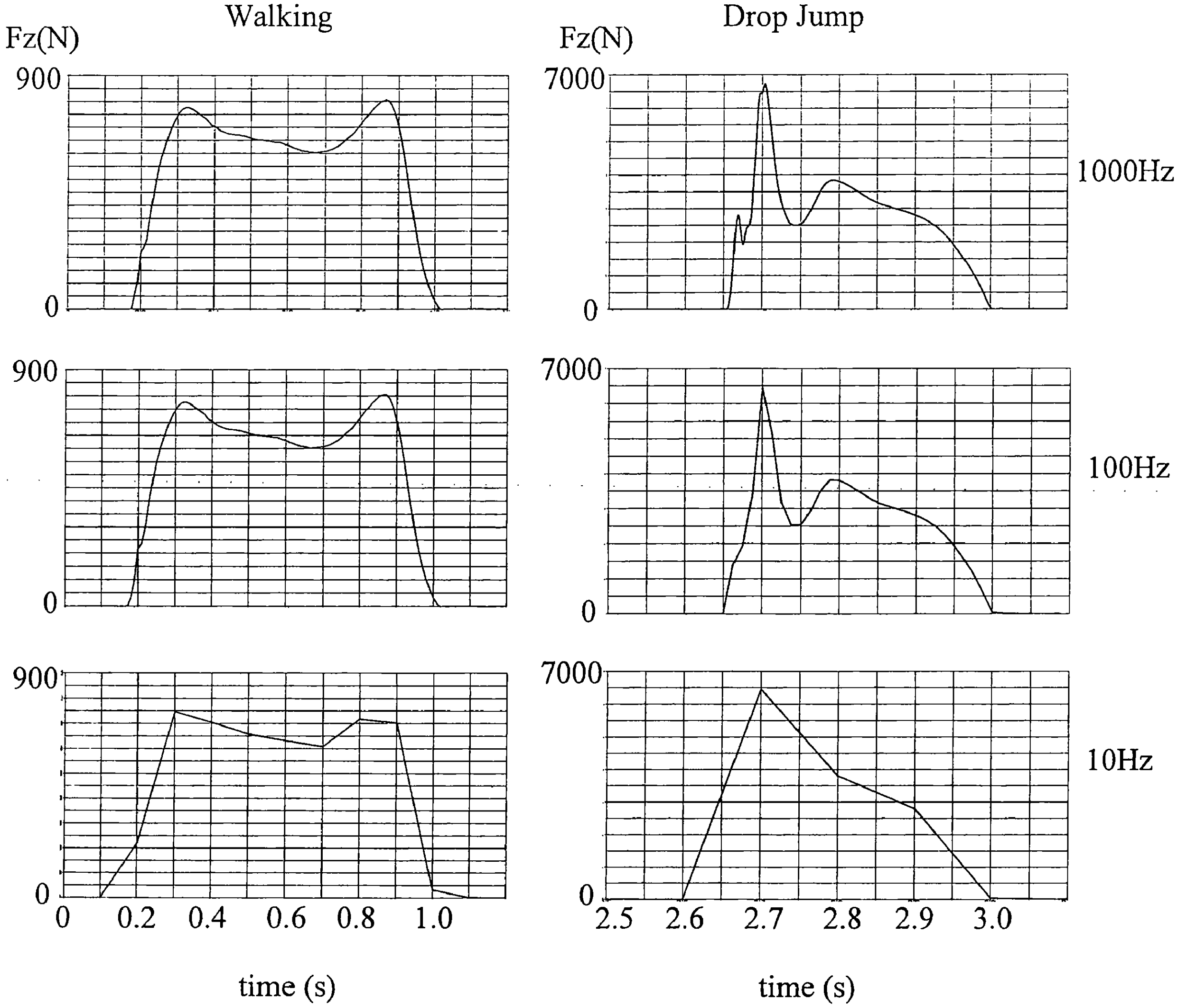


Figure 2.7 Vertical ground reaction force-time histories for walking and landing from a drop jump collected sample rates of 10, 100 and 1000 Hz.

rate that is high enough to provide an accurate force-time history of an event, for example running or jumping, to be recorded. Figure 2.7 illustrates how the force-time record of two different events, walking and a drop jump, are affected by different sampling rates. The top graphs are sampled at 1000 Hz, the middle graphs at 100 Hz and the bottom graphs at 10 Hz. The graphs on the left are force-time histories of a subject walking over the force platform at approximately 1 $m.s^{-1}$ and the graphs on the right are force-time histories of a subject performing a drop jump, onto the force platform, from a 60 cm box. Inspection of the 1000 Hz and 100 Hz graphs for walking reveals no perceivable differences in the shape of the graphs. However if the corresponding drop jump graphs are inspected it is clear that whilst the shapes of the graphs are similar, some detail has been missed when sampling at 100 Hz compared to when sampling at 1000 Hz. The small drop in force that occurs between 2.6 s and 2.7 s on the 1000 Hz graph is missing on both the 100 Hz and 10 Hz graphs. The reason for the differences in the drop jump graphs is that the forces involved in drop jumping change rapidly and a sample rate of 100 Hz, or 10 Hz, is insufficient to accurately reflect the true force-time history as any force changes that occur between samples i.e. within 1/100th s of each sample, are effectively invisible. A similar situation occurs with the walking graphs recorded at 10 Hz and 100 Hz. A peak that occurs between 0.8 s and 0.9 s on the 100 Hz graph is missing on the 10 Hz graph. Sampling at 10 Hz only allows the force platform system to record the force at 0.8s (effectively instantaneously) and again at 0.9s (effectively instantaneously), missing any changes that had occurred between these two points. The resulting force-time history is then represented as a straight line between 0.8 s and 0.9 s, thus missing the actual peak.

The usual procedure to determine the appropriate sampling rate for a periodic signal would be to initially determine the highest frequency contained in the signal using Fourier analysis. The sampling rate could then be determined on the basis of Nyquist's sampling theorem (Nyquist 1928) which states that a sampling frequency of double the highest frequency contained in the signal to be sampled is necessary to ensure that none of the original signal is lost during the sampling process and that aliasing does not occur. Sampling at higher frequencies that those determined by the Nyquist sampling theorem, over sampling, would have the benefit of achieving improved temporal resolution, however this benefit might be offset by the greater chance of degrading the signal being sampled by introducing noise into the extended bandwidth.

These two examples illustrate the need to choose a sampling frequency that is appropriate for the activity under consideration. The sample rate needs to be high enough to record the fastest changing force values and accurately determine events, such as the instant of take-off for a jump. However an unnecessarily high sample rate will increase the amount of data generated and use more computer memory for storage than is necessary. This would cause analysis to take longer than it otherwise would especially if it was an analysis using a spreadsheet. For example if the 1000 Hz force-time history for walking was used for analysis it is unlikely that more useful information would be gained compared to if the 100 Hz force-time history had been used. However, 10 times more data would have been collected and stored than was actually necessary. Conversely if the 100 Hz force-time history of the drop jump was used for analysis, potentially important information would not have been recorded.

2.5 Measurement of mechanical power of the vertical movement of the whole body centre of gravity in a countermovement jump

Attempts to measure mechanical power produced by the legs in a vertical jump date back to Sargent (1924) who proposed that the product of the height jumped performing a vertical jump and a subject's weight, normalised to stature, was a measure of leg power. Whereas the product of body weight, W, and height jumped, h, is a reasonable (depending upon the accuracy of the measurement of h) estimate of the change in the gravitational potential energy (estimated work done) of the body, the term $W.h.S^{-1}$, where S = stature, is not a measure of power (rate of change of work) and Sargent (1924) did not provide any information on the validity of the term. Many years later, Gray et al. (1962) presented a method of measuring average leg power, termed the vertical power jump, based on the change in gravitational potential energy during the propulsion and flight phases in a jump and reach test, that was mechanically valid. In this method, average leg power was measured as, $W.h/t$, where W = body weight, h = jump height and t = propulsion time. Figure 2.8 shows the three positions, of a squat jump, termed the power jump, from which Gray et al. (1962) derived their expression for average leg power. The distances h_1 and h_2 were determined by the subject marking an adjacent wall or board with their chalked finger tips, initially in the squat position with their arm outstretched vertically above their head, for position 1, Figure 2.8, then on tiptoes, with their arm outstretched vertically above their head, for position 2, Figure 2.8. Once the marks for position 1 and position 2 had been made, the squat position was re-assumed and the jump performed. The subject would then make a third mark on the wall or board, corresponding to their finger tip's position at the peak of their jump. The total work done (change in gravitational potential energy between positions 2 and 3) for the jump was then calculated as: work done = $W.(h_1 + h_2)$. ---------- 2.1

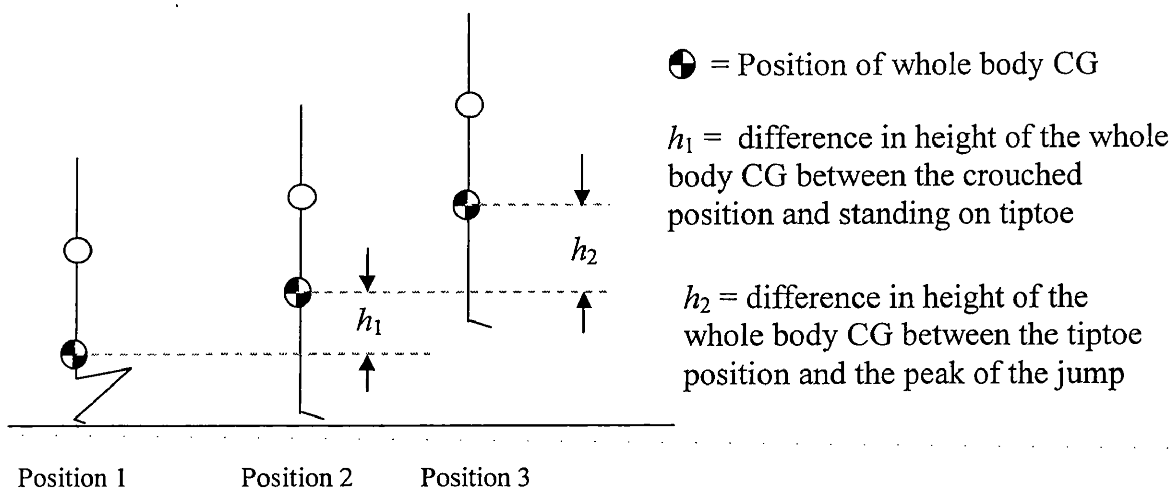


Figure 2.8: Estimation of vertical displacement of the whole body centre of gravity in the vertical power jump of Gray et al. (1962).

The time taken to move from position 1 to position 2 was then determined, using the equations of motion for uniform acceleration, as:

$$t = h_1\sqrt{\frac{2}{g.h_2}} \quad \text{-----------------------------------} \quad 2.2$$

g = acceleration due to gravity

Finally power was determined by application of equation 2.3:

$$\text{power} = \frac{W(h_1 + h_2)}{h_1} \cdot \sqrt{\frac{g.h_2}{2}} \quad \text{-------------------} \quad 2.3$$

Even though their formula used the correct physical units it was limited by the assumptions that there was no relative motion between the CG and the tips of the fingers in a squat jump and that the acceleration during the propulsion phase of a squat jump was constant. The relative position of the CG with respect to the tips of the finger, with an arm vertically outstretched, clearly changes during a squat jump as the relative position of body segments changes. As the position of the outstretched arm remains fixed, in relation to the trunk, then the relative position of the CG with respect to the tips of the fingers has to change. The vertical acceleration of the CG is directly proportional to the vertical ground reaction force and therefore has the same shape time history as the vertical ground reaction force-time history. Inspecting this profile for the propulsion phase of a countermovement jump, points B to D Figure 2.3, reveals that the acceleration is clearly non-uniform.

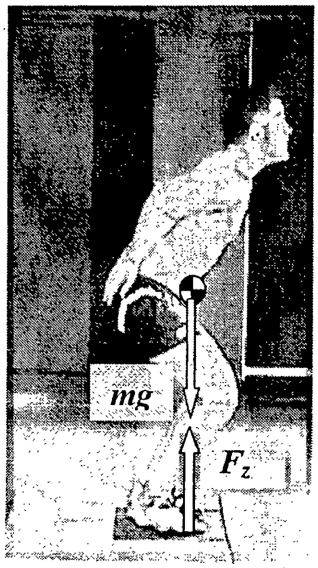
Whereas the vertical power jump of Gray et al. (1962) provides an estimate of average leg power, Davies and Rennie (1968) proposed a method of measuring instantaneous vertical mechanical power output of a countermovement jump by means of a force platform. Their equipment consisted of a force platform which produced an analogue signal via an amplifier. The amplified analogue signal was then input into a chart plotter, an electromechanical output device, which Davies and Rennie described as having a scale of 0.02 s. A scale of 0.02 s would be equivalent to a digital computer sampling at 50 Hz. Instantaneous mechanical power, P, was calculated by determining the vertical acceleration of the CG of a subject from the vertical ground reaction force as measured by a force platform and then integrating it with respect to time to give instantaneous velocity. Instantaneous mechanical power was then given by the product of instantaneous vertical ground reaction force, F, and instantaneous vertical velocity, v, of the CG i.e. $P = F.v$. The results are shown in Table 2.2.

Subject	N	Age ± S.D. (yr)	Mass ± S.D. (kg)	Height ± S.D. (cm)	Power ± S.D. (W)
Male	47	32.7 ± 8.9	74.9 ± 10.0	172.9 ± 6.6	3901 ± 888
Female	8	22.1 ± 3.9	60.0 ± 7.5	163.5 ± 6.0	2350 ± 358

Table 2.2: Results of the measurements of instantaneous vertical mechanical power output of a countermovement jump, Davies and Rennie (1968)

The force platform method of measuring instantaneous mechanical power has become the accepted method (criterion measurement for assessing the validity of indirect measures) when evaluating vertical jumps (Harman et al. 1991; Johnson and Bahamonde 1996; Sayers et al. 1999; Hertogh and Hue 2002; Shetty 2002; Canavan and Vescovi 2003; Lara et al. 2006). This method requires a subject to perform a vertical jump on a force platform. The vertical ground reaction force-time history of the jump is recorded. These force data are in the form of a time array of discrete force values as opposed to a continuous analogue function that could be described by an equation. Consequently the use of standard integrals to determine the area under the graph (integration) of the force-time history is not possible. To find the area under a force-time history described by digital values it is necessary to utilise numerical integration (Kibele 1998). Numerical integration of the net vertical force-time history, divided by mass, produces the instantaneous vertical velocity of the whole body CG. The corresponding instantaneous mechanical power, for a time, t, is given by the product of force and velocity at that time, t i.e. $P_t = F_t.v_t$. This can be represented mathematically using Newton's second law (Hatze 1998). Figure 2.9 shows the external forces acting on a subject prior to take-off in a countermovement jump. For some time, t, the vertical velocity of the CG, v_{zt}, is determined by integrating the acceleration of the CG and adding the value to the velocity at the start of the jump, v_{zts}.

$$v_{zt} = v_{zts} + \int_{t_s}^{t} \frac{F}{m} - g.\mathrm{dt} \qquad \text{----------} \quad 2.4$$



⊕ = whole body centre of gravity

m = subject's mass (kg)

g = acceleration due to gravity (m.s^{-2})

F_z = vertical ground reaction force (N)

Figure 2.9 External forces acting on a subject prior to take-off in a countermovement jump, whole body weight = $m.g$

For some time, t, the vertical displacement of the CG, s_{zt}, is determined by integrating the velocity of the CG and adding the value of the displacement at the start of the jump, s_{zts}.

$$s_{zt} = s_{zts} + \int_{t_s}^{t} v_z.\mathrm{dt} \qquad \text{-------------} \quad 2.5$$

Power then equals, $P_t = F_{zt}.v_{zt}$ ------- 2.6

The relationship between vertical ground reaction force, vertical velocity and mechanical power for a subject performing a countermovement jump is shown in Figure 2.10.

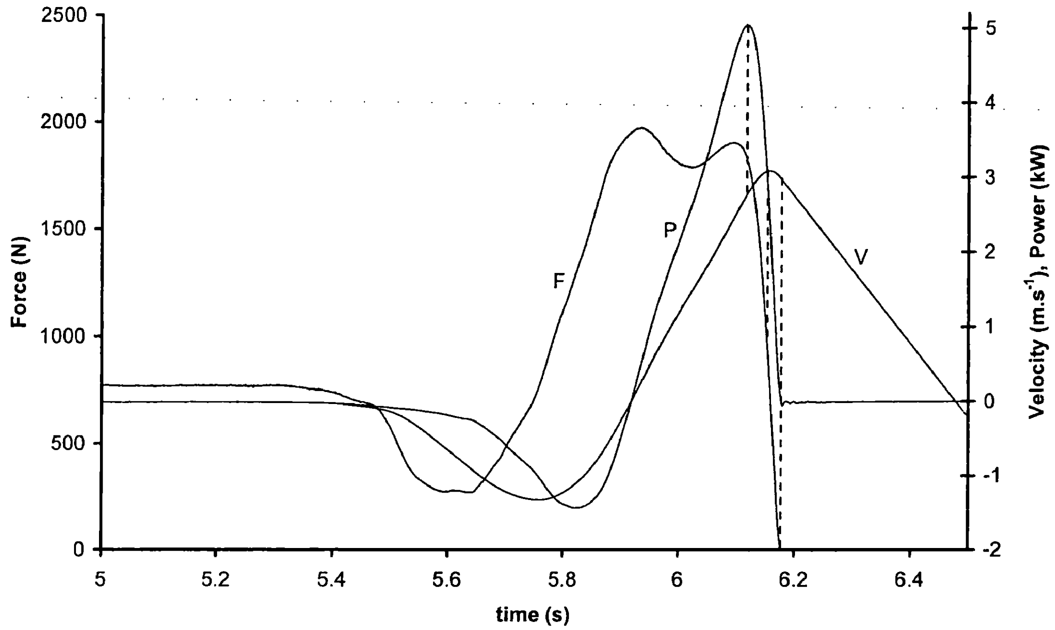
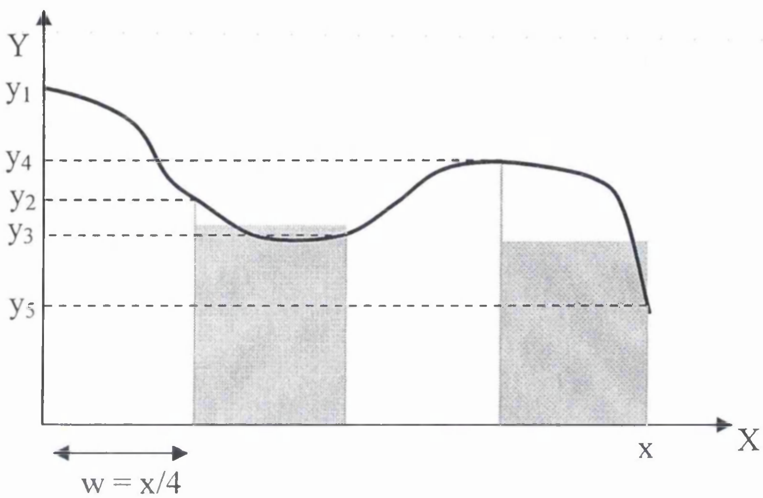


Figure 2.10 Relationship between vertical ground reaction force (F), vertical velocity (v) and mechanical power (P) for a subject performing a countermovement jump. The dotted lines indicate, from left to right, the position of peak power, peak velocity and the instant of take-off.

2.5.1 Numerical integration.

A force platform system can be used to record a force-time history, which in turn can be used to analyse different events which are of interest to a biomechanist. For example force-time histories might be for a subject walking, jumping or maintaining a balanced stance. When the force-time has been recorded it is often necessary to determine physical quantities other than force, such as acceleration, velocity or displacement. Figure 2.3 shows a subject performing a vertical countermovement jump and the relationship between vertical ground reaction force, vertical velocity and vertical displacement of the subject's whole body centre of gravity, for a subject of mass, *m*. Equations 2.4 and 2.5 describe how vertical velocity and vertical displacement are determined from the vertical ground reaction force, *F*z, measured at the subject's point of contact with the force platform, his feet. To determine the subject's vertical velocity it is necessary to integrate the expression, $(F_Z - m.g)/m$, numerically (Kibele 1998). Integration is a process which allows the area under a graph (between the graph and the x axis) to be calculated. If the graph can be described by an algebraic equation, then often standard integrals can be used to evaluate the area under the graph. When this is not possible, for example when an equation doesn't have a standard integral or no equation is known, then other methods need to be used. There are a number of other methods for calculating the area under a graph, the simplest of which involves drawing a grid over the force-time graph that corresponds to the units being used (force in newtons and time in seconds) and counting the whole number of grid rectangles and estimating the part rectangles. This method can be accurate if the graph is large relative to the size of the grids. However, it is a very time consuming process. The usual method now employed to estimate the area under a force-time curve is numerical integration. The two methods of numerical integration that are normally used are the trapezoidal rule and Simpson's rule (Kibele 1998). To find the area under a graph using the trapezoidal rule, the area is divided into a number of equal strips, the area of each strip is then approximated to the area of the trapezoid formed by the strip and the value of the curve at the top of the strip's ordinates. The sum of these trapezoids then gives an approximation to the area under the graph. Simpson's rule gives a better approximation of the area that the trapezoidal rule if the same number of strips are used. The area under a curve, using Simpson's rule, needs an even number of strips and is given by the area, A = 1/3 strip width x [(sum of the first and last ordinates) + 4(sum of the even ordinates) + 2(sum of the remaining odd ordinates)], Figure 2.11.



Trapezoidal rule area = $\frac{1}{2}$ w(y_1 + y_2) + $\frac{1}{2}$ w(y_2 + y_3) + $\frac{1}{2}$ w(y_3 + y_4) + $\frac{1}{2}$ w(y_4 + y_5) -------- 2.7

Simpson' rule area = 1/3 w[(y_1 + y_5) + 4(y_2 + y_4) +2(y_3)] ------------------------------------- 2.8

Figure 2.11 Examples of the use of the trapezoidal rule and Simpson's rule to determine an approximate area under a curve.

Simpson's rule achieves better accuracy than the trapezoidal rule by fitting a curve to the end points of each pair of adjacent strip's ordinates (Booth 1995). Figure 2.12 shows two graphs of the same equation, $F_z(t) = 100.\sin(\pi.t)$, between a time, t = 0s to t = 1s. The graphs are sinusoidal force-time graphs having a maximum force value of 100 N and duration of 1 s. The equation that describes this graph, $F_z(t) = 100.\sin(\pi.t)$, can be integrated using standard integrals to give an exact value for the area under the graph:

$$\int_0^1 00.\sin(\pi.t)dt = - \left[\frac{-100\cos.t}{\pi}\right]_0^1 = 63.66 \text{ N.s} \quad \text{----------} \quad 2.9$$

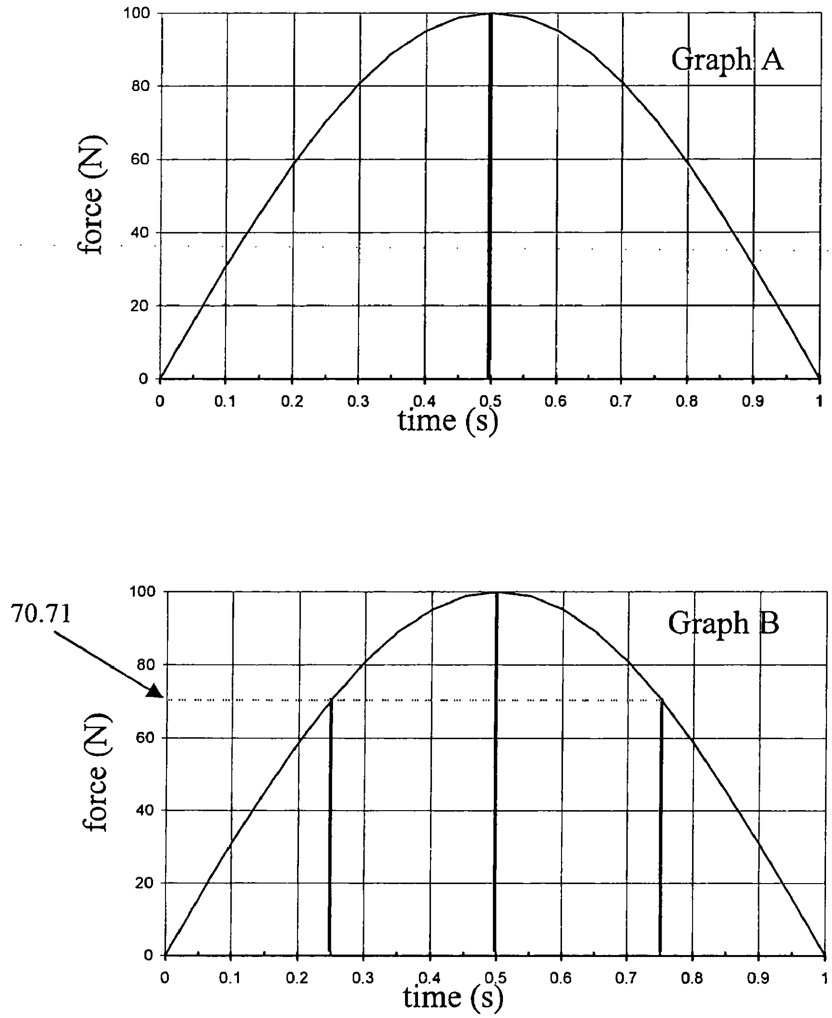


Figure 2.12 Graphs of the equation $F_z(t) = 100.sin(\pi.t)$ between times of 0 s and 1 s. Graph A is divided into two equal strips and graph B into four equal strips.

The two graphs, A and B, in Figure 2.11 are identical and can be used to demonstrate the accuracy of the trapezoidal rule and Simpson's rule in finding the area under the graph of $F_z(t) = 100.sin(\pi.t)$. Graph A in Figure 2.11 is divided into two equal strips of width = 0.5s. Applying the trapezoidal rule (equation 2.7) the area is given by:

Area = ½ .0.5(0 + 100) + ½ .0.5(100 +0) = 50 N.s

Applying Simpson's rule (equation 2.8) the area is given by:

Area = 1/3 .0.5[(0 + 0) + 4(100) = 66.67 N.s

Graph B in Figure 2.11 is divided into four equal strips of width = 0.25s.

Applying the trapezoidal rule (equation 2.7) the area is given by:

Area = ½ .0.25(0 + 70.71) + ½ .0.25(70.71 + 100) + ½ .0.25(100 + 70.71)
+ ½ .0.25(70.71 + 0) = 60.35 N.s

Applying Simpson's rule (equation 2.8) the area is given by:

Area = 1/3 .0.25[(0 + 0) + 4(70.71 + 70.71) + 2(100) = 63.81 N.s

Actual value of area = 63.66 N.s (using analytical integration)

Simpson's rule usually estimates the area with less error than the trapezoidal rule, however in practice this isn't necessarily a problem as to increase the accuracy of the trapezoidal rule it is only necessary to increase the number of strips used to estimate the area. The number of strips is determined by the sample rate of the force platform system and the length of force-time history that is being considered.

2.6 Comparative analysis of existing force platform studies that measure vertical mechanical power of a countermovement jump

The method described by Davies and Rennie (1968) has become the criterion method for the determination of instantaneous mechanical power of a countermovement jump (Harman et al. 1991; Johnson and Bahamonde 1996; Sayers et al. 1999; Shetty 2002; Canavan and Vescovi 2003; Lara et al. 2006). Even though the force platform method of measuring mechanical power has been accepted as the criterion protocol there appears to be no standard, accepted method for the collection of vertical ground reaction force-time data and its subsequent analysis. The main variables that are likely to affect the accuracy of velocity and displacement data obtained by the integration of force-time data are listed in Table 2.3 together with descriptions of the ways in which the variables have been addressed in three frequently reported studies. It is clear from Table 2.3 that there is little information on the methods used in these three studies. Kibele (1998) reported that the use of the trapezoidal rule is a convenient method of integration and that Simpson's rule would hold no benefits over its use if the integration frequency was 1000 Hz (the frequency at which he collected and integrated data) but no reference is made to the accuracy of higher or lower frequencies of integration. The author reports that an error of 5 - 10 ms in the identification of the onset of movement of a jump would only cause a 0.1% error in velocity or displacement values as the rate of change of force at this time would be low; but presented no supporting evidence. Regarding the identification of the instant of take-off the author reports that an error of 2 - 3 ms would cause an error of up to 2% in the determination of velocity and displacement as the rates of change of force would be higher at this time,

	Recommended variable value or method of determining variable		
Variable	**Kibele (1998)**	**Hatze (1998)**	**Vanrenterghem (2001)**
Sample frequency and resolution	1000 Hz at 12 bits	2000 Hz, resolution not considered	100 to 1000 Hz no single frequency was identified as recommended, resolution not considered
Integration frequency	Not stated	2000 Hz	100 to 1000 Hz no single frequency was identified as recommended
Method of integration	Trapezoidal rule	Not stated	Trapezoidal rule
Determination of body weight	Difference between stance phase and airborne phase of jump's force values	Not stated	By adjusting the value of BW during the stance phase until the displacement of the CG at the end of the stance phase equalled its value at the beginning.
Determination of initiation of jump	Determined by software – methods not stated	Determined by software – methods not stated	Time, after stance phase, when force value exceeded the preceding five force samples' mean by a set multiple of ± SD's.
Determination of instant of take-off	Determined by software – methods not stated	Determined by software – methods not stated	Not stated

Table 2.3. Variables that affect quality of velocity-time and displacement-time data derived from integrating force-time data.

but no supporting evidence was presented. These time events, the initiation of the jump and the instant of take-off, were determined by software in Kibele's (1998) investigation but algorithms or definitions of the conditions were not stated. Hatze (1998) used a sampling and integration frequency of 2000 Hz and estimated, through mathematical error analysis, that the integration of his data would produce an error of no more than 0.41% in the evaluation of velocity but the method of integration was not reported. The author didn't describe the methods used to determine jump height or instantaneous power. Vanrenterghem (2001) investigated four of the variables in Table 2.3 as possible sources of error in the determination of jump height using a force platform and the double integration method. These variables also have a direct application in the determination of instantaneous power of a vertical countermovement jump. By using a theoretical model of the vertical ground reaction force-time history of a countermovement jump (constructed from a succession of sinusoidal and linear equations) and applying analytical double integration, it was possible to compare these results with those of numerical integration of the same ground reaction force-time history model. Using different frequencies of numerical integration it was possible to systematically vary, and consequently determine the effect of changes in the integration frequency on the velocity-time and displacement-time graphs produced by numerical methods. The results obtained by numerical integration could then be compared to the results obtained by analytical integration. Using the same theoretical model, the effect of incorrect body mass, incorrect determination of instant of take-off and incorrect determination of initiation of the jump on jump height were investigated.

Prior to using the theoretical model it was necessary for Vanrenterghem (2001) to define a protocol for the determination of body weight. He recommended that body mass and, therefore, body weight should be determined separately for each jump as he reports an inter-trial variation of body mass of 1.3 kg. It is however unlikely that body mass would change this much between trials but it is possible that the measurement of this value could alter due to drift in instrumentation. Vanrenterghem identified that the determination of vertical velocity and vertical displacement by integration of the resultant vertical force-time history is very sensitive to variations in body weight and as such measuring body weight for each trial is therefore necessary, however he presented no evidence in support of this. To determine body weight Vanrenterghem adjusted its value, as a variable of integration, such that after a 2 s stance phase, just prior to a countermovement jump, there would be a no change in the vertical displacement of the whole body centre of gravity, as compared to the start of the stance phase. Relative null vertical displacement of the whole body centre of gravity was achieved by repeated double integration of the resultant vertical force-time history, varying the body weight after each iteration. The adjusted value of body weight that produced a null displacement, of the whole body centre of gravity, at the end of the stance phase, relative to the start, was then taken to be the correct value. He states that null displacement between the start and end of the 2 s stance phase fulfils the initial conditions of null displacement and velocity. However null relative displacement at the end of the stance phase does not imply zero velocity. In fact unless the actual displacement and velocity at the start of the stance phase were the same as at the end of the stance phase, then using the method described by Vanrenterghem would give an incorrect value of body weight, as illustrated in Figure 2.12. The condition that there are no unbalanced impulses present in the stance phase of a countermovement jump is unlikely as even when a subject stands "perfectly" still there is always slight vertical oscillation of the whole body centre of gravity due to breathing and pendular sway of the whole body centre of gravity over the feet in order to actively maintain balance. If a subject could stand perfectly still on a force platform during the stance phase, the only variation in the vertical ground reaction force would be that due to noise present in the force signal. In this situation, the average magnitude of the vertical ground reaction force would represent the true value of body weight (the noise, being random would cancel itself out), assuming that the force platform was correctly calibrated. In this situation adjusting the value of body weight to obtain zero velocity and relative zero displacement, after double integration of the vertical ground reaction force over the stance phase, would correctly identify the subject's actual body weight. However this would be the same as the value obtained by averaging the force value over the stance phase as one is derived from the other. It would therefore seem logical to determine body weight by averaging the vertical ground reaction force values over the stance phase of a countermovement jump as if this average was actually incorrect then so would the subsequent values of vertical ground reaction force during the countermovement jump.

With regard to initiation of movement, Vanrenterghem (2001) recommended a method that determined the average of 5 successive ground reaction force samples and compared this with threshold values. The threshold value was the mean ground reaction force during the 2 s stance phase immediately prior to the countermovement jump, plus or minus a multiple of standard deviations. This criterion starts in the stance phase and shifts forward in steps of one sample until

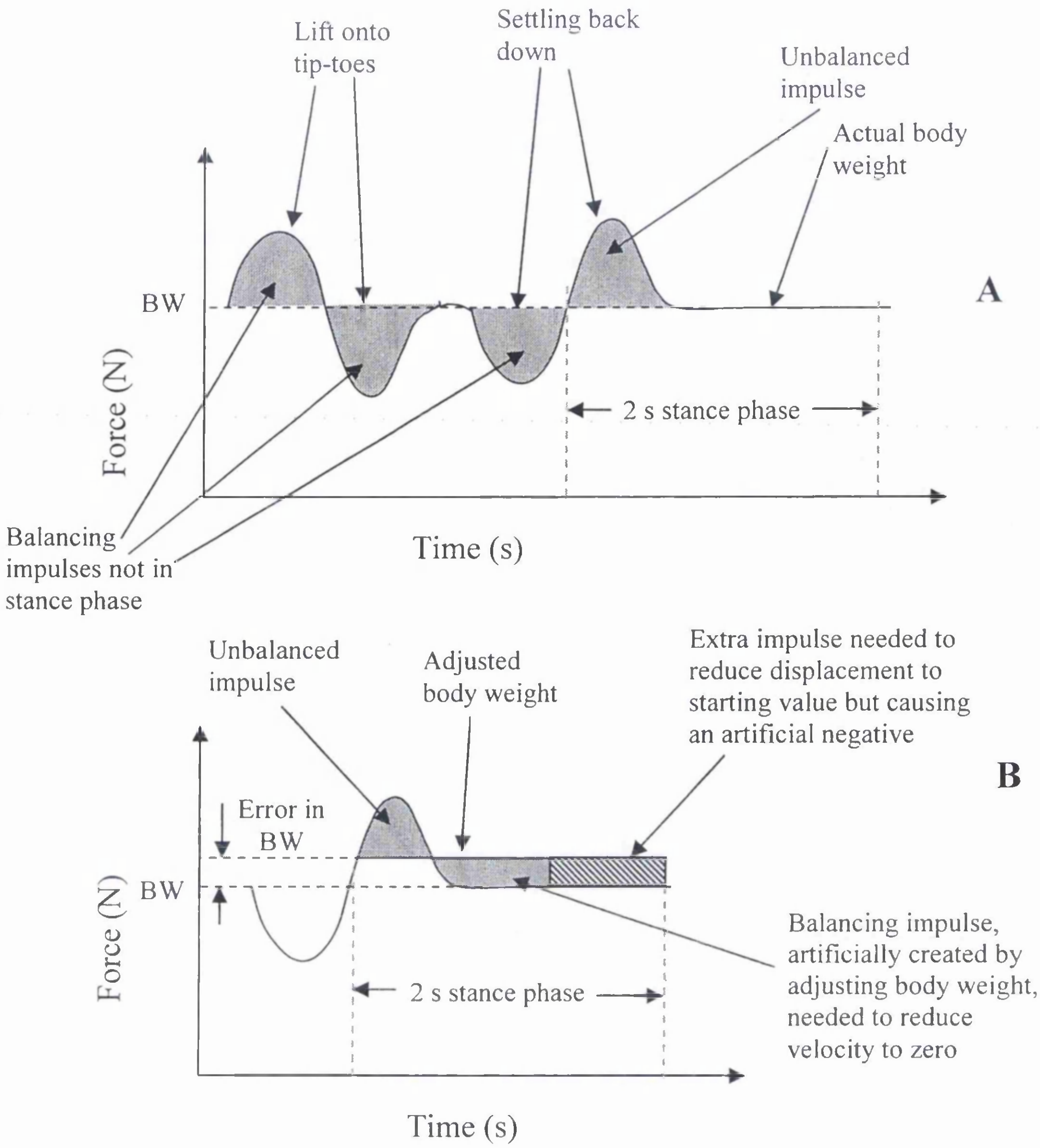


Figure 2.13 Illustration of the effect of an unbalanced impulse being included in the stance phase of a countermovement jump on the determination of body weight (BW) using the method described by Vanrenterghem (2001). Graph A shows the actual situation of a subject lifting themselves up on tip-toes and then settling back down, graph B shows the result of the 2 s stance phase including an unbalanced impulse; the body weight is adjusted such that the shaded areas above and below the adjusted value of BW are the same resulting in zero velocity but causing an artificial displacement. The cross-hatched area is the impulse needed to cancel out the artificial displacement of the whole body centre of gravity so that null displacement is achieved at the end of the stance phase, however this would also creates an artificial velocity.

the average exceeds the threshold; this point is then defined as the initiation of the jump. No threshold values were recommended by Vanrenterghem. Ideally the initiation of a jump would be defined as the time, immediately prior to a change in force, greater than the threshold value, being detected at which the ground reaction force is equal to body weight. However, Kibele (1998) suggested, in practice the rate of change of force at the beginning of a jump is low and errors of 5 - 10 ms do not change velocity or displacement parameters by more than 0.1%, thus allowing a degree of latitude in the identification of initiation of movement. Consequently any protocol that uniquely identifies the initiation of a jump, such that the differences in the values of the velocity and consequently power, as measured by using the ideal initiation time and the detected initiation time are within the required accuracy limits, can be considered acceptable. Vanrenterghem's proposed method of determining the initiation of a jump is logical and repeatable. It can also be adjusted in terms of sensitivity, to accommodate varying levels of noise in the force signal, by varying the threshold values.

Vanrenterghem (2001) reported deviations in reach height or flight height (h_r and h_2 ,Figure 2.1) of 0.9 cm due to an error of 3 ms in the determination of the instant of take off, but these errors tend to cancel each other out such that the overall error in jump height ($h_j = h_r + h_2$, Figure 2.1)is in the region of 0.02 cm. However the meaning of a variation of 0.02 cm in jump height is questionable. Locating the whole body centre of gravity to 0.2 mm has little meaning (a shrug of the shoulders or inhalation could cause a change of this magnitude, if it could actually be measured) therefore this purported level of precision seems questionable.

Finally Vanrenterghem (2001) considered integration frequencies and associated errors. Comparisons were made between h_r and h_2 calculated by the analytical integration of the theoretical model against h_r and h_2 calculated by numerical integration of the same model. The results showed that the frequency of numerical integration resulting in the most accurate estimation of h_r and h_2 was 1000 Hz and that the frequency of integration resulting in the least accurate estimate of h_r and h_2 was 50 Hz, with the greatest variation in error occurring at a frequency of integration of 100 Hz. Vanrenterghem reported that a comparison of integrating the derived acceleration signal both analytically and numerically, at 1000 Hz, revealed differences in jump parameter outcomes of less than 0.1mm, however he didn't identify these parameters. Integration frequencies of 100 Hz or more were reported to have errors in the determination of h_r and h_2 of less than 0.1 mm. The least accurate result, occurring at an integration frequency of 50 Hz, was reported to have errors of less than 0.4 mm for h_r and less than 0.3 mm for h_2. However as the scale on Vanrenterghem's Figure 2, appears to be incorrect the accuracy of the reported values is not clear. If a numerical integration frequency of 50 Hz produces an error of only 0.4 mm and a frequency of integration of 1000 Hz an error of 0.1 mm there would be effectively no difference in the accuracy of these frequencies as it is not feasible to measure the position of the whole body centre of gravity to this level of precision. Also if a frequency of integration of 50 Hz were used and assuming that the sampling frequency was the same, the instant of take-off could only be measured with a precision of less than or equal to ± 20 ms and the same would be true for the initiation of the jump. However Vanrenterghem also states that a 3 ms error in the identification of the instant of take-off produced a deviation of 9 mm in h_r and h_2. Clearly these two conditions are mutually exclusive.

2.7 Comparative analysis of studies that estimate mechanical power of the human body in a vertical countermovement jump

The product of vertical ground reaction force and vertical velocity of the centre of gravity (derived from the ground reaction force) is generally regarded as the criterion measure of power output in a vertical countermovement jump. However force platforms are expensive and not readily available outside a laboratory setting. Consequently attempts have been made to estimate mechanical power output in a countermovement jump from other, more easily measured variables. The variables most frequently used in regression equations to estimate mechanical power output in a countermovement jump are the subject's mass, standing height and jump height (Harman et al. 1991, Johnson and Bahamonde 1996, Sayers et al. 1999, Shetty 2002, Canavan and Vescovi 2003, Lara et al. 2006). Table 2.4 lists a number of regression equations reported in the literature that estimate mechanical power output in a vertical jump together with mean data for particular populations. Table 2.5 summarises the methods used in these studies.

Fox and Mathews (1974) reported the "Lewis formula" (no reference is given for this formula) as a measure of power in a vertical jump when "starting from a crouched position". Fox and Mathews did not specify whether the formula estimated peak or average power, but the outcome measure is in $kg.m.s^{-1}$, which is not a unit of power. The formula was originally intended for use with a jump and reach board. Jump height was defined as the difference in height between the highest point that a subject could reach to on the jump and reach board while keeping their heels on the floor and another mark made on the board at the peak of their jump. No instructions were given about the use of arm swing in the jump. This formula, corrected (by using the subject's weight in newtons rather than mass in kilograms), has been extensively used as if it were a regression equation to predict peak power (Harman et al. 1991; Johnson and Bahamonde 1996; Sayers et al. 1999; Hertogh and Hue 2002; Shetty 2002; Canavan and Vescovi 2003; Lara et al. 2006). However, analysis of the Lewis formula by Harman et al. (1991) showed that, even when corrections were made to the formula to produce an outcome measure in units of power, it actually measures the average power of the subject's weight falling back to the ground, under the influence of gravity, from the peak of their jump. Consequently, the Lewis formula has no content validity as a measure of power output in a vertical jump. It has been shown to have a high correlation with the criterion force platform method, but not agreement (underestimating peak power by approximately 70% and underestimating average power by approximately 20%). There have been no reported studies of attempts to validate the formula in relation to the criterion force platform measure.

Harman et al. (1991) developed two regression equations, each with two variables, to estimate peak and average power of a vertical jump using 17 male subjects (age = 28.5 ± 6.9 years, mass = 74.7 ± 7.7 kg). No information on the training status or sporting background of the subjects was provided. Canavan and

Vescovi (2004), using power and effect size, indicated that a sample of at least 25 subjects was necessary to develop a regression equation for the determination of power output in a vertical jump. Consequently, Harman et al.'s sample size of 17 subjects is a limitation in their study. The two variables used by Harman et al. (1991) in both regression equations were body mass and jump height as determined in a jump and reach test; their prediction equation for peak power and their results for this equation are listed in Table 2.4. Subjects first performed maximal jumps in a jump and reach test, in which jump height was defined as the difference in the height of marks made on a wall whilst reaching as high as possible with their feet flat on the floor and marks made at the peak of the jump after starting from a stationary squat position. Their criterion measure of instantaneous power was determined by the criterion force platform method using the force-time record of a second maximal jump. Force-time histories were collected at 500 Hz and converted into digital values using a 12 bit analogue to digital converter. The product of instantaneous vertical ground reaction force and instantaneous vertical velocity of the centre of gravity (equation 2.6) was used to determine instantaneous power throughout the jump. However the method of integration and definition of initiation of the jump were not reported. As the velocity-time data derived from the force-time data is likely to be significantly affected by the method of integration and definition of the initiation of the jump, the validity of the criterion measure of power output used in the Harman et al. study is not clear and, consequently, the validity of the regression equation is not clear. In addition to the method of integration and the definition of the initiation of a jump, the frequency of integration would also affect the validity of the criterion force data and, consequently, the regression equation. These authors integrated

Author (type of jump)	Regression equation (peak or average power)	Criterion mean power Results (W)	Regression equation mean power Results (W)
Fox and Mathews' 1974 Lewis formula[1] (not stated)	P = 9.8√(4.9).(M).√(H) (not stated)	NA	NA
Harman et al. 1991 (SJ)	Pp = 619(H) + 36(M) + 1822 (peak power)	3767	Mean not reported ($r = 0.88$, S.D. = 603W)
Johnson and Bahamonde 1996 (CMJ)	Pp = 785(H) + 60.6(M) – 15.3(S) -1308 (peak power)	4707	4687 ($R^2 = 0.91$ SE = 462W)
Sayers et al. 1999 (CMJ)	Pp = 519(H) + 48.9(M) – 2007 (peak power)	Mean not reported	% diff = 2.7% ($R^2 = 0.78$ SEE = 561.5 W)
Shetty 2002 (CMJ)	P = -666.3 + 14.74(M) + 1925.72(H) (not stated)	1458	1451 ($R^2 = 0.69$ ($p<0.05$), S.D. = 222 W)
Canavan and Vescovi 2003 (CMJ)	Pp = 651(H) + 25.8(M) – 1413.1 (peak power)	2425	2406 ($R^2 = 0.92$ ($p<0.000$), SEE = 120.8 W)
Lara et al. 2006 (CMJ)	Pp = 625(H) + 50.3(M) – 2184.7 (peak power)	3524	3624 (no sig. diff.($p<0.05$) SEE = 246.5 W)

H = height jumped (m) CMJ = countermovement jump
Pp = peak power P = power
M = body mass (kg) SJ = squat jump
S = stature (m) R^2 = coefficient of determination
SD = standard deviation SEE = standard error of the estimate
SE = standard error r = correlation coefficient

1. The Lewis formula is not a regression equation but it has been used as such in numerous previous studies and is therefore included for completeness.

Table 2.4 Regression equations and mean data from previous studies of power output in a vertical jump.

the force-time history of the jumps at a frequency of 20 Hz, which equates to an uncertainty in the initiation of the jump of at least ± 50 ms. Uncertainties of this magnitude would also render the measurements of power invalid as accepted values of uncertainty for the initiation of a jump are almost a factor of ten smaller (Kibele 1998; Vanrenterghem 2001). Furthermore, any changes in the value of instantaneous power within the integration width would be missed. The measures used in the criterion and predictor methods should be determined from the same jump (jump simultaneity); that is, the predictor jump should be performed on the force platform such that the criterion measure of power and the predictor jump height are determined from the same jump. This limitation was also recognised by Harman et al. and they made a recommendation for criterion and predictor jump simultaneity. A summary of the parameters, variables and definitions used to measure and to estimate power in a vertical jump in previous studies, including Harman et al.'s, are listed in Table 2.6.

The remaining studies (Johnson and Bahamonde 1996, Sayers et al. 1999, Shetty 2002, Canavan and Vescovi 2003, Lara et al. 2006) all estimated peak power of countermovement jumps as opposed to an estimate of power of a squat jump by Harman (1991). All these studies used a sampling frequency of 500 Hz, except Shetty (2002) who used 100 Hz, and the product of instantaneous vertical ground reaction force and instantaneous vertical velocity of the centre of gravity (equation 2.6) to determine instantaneous power throughout the jumps. Previous studies have recommended sampling frequencies of at least 1000 Hz (Kibele 1998, Hatze 1998) but the effect of sampling at lower frequencies was not reported. Methods of integration, frequency of integration and definitions of initiation of jumps were not reported in any of the studies. As the velocity-time data derived from the force-time data are likely to be significantly affected by the frequency of integration, method of integration and the definition of the initiation of the jump, the validity of the criterion methods used in these studies is not clear and,

Study (type of jump)	**Subjects**	**Description of Criterion method**	**Predictor jump method**
Harman et al. 1991 (SJ)	17M (age = 28.5 ± 6.9, mass = 74.7 ± 7.y kg)	Force platform 500 Hz, $P_i = F.v$ Integrated at 20 Hz	Jump and reach
Johnson and Bahamonde 1996 (CMJ)	69M and 49F college mixed athletes (age = 19.58 ± 1.24 yrs, mass = 73.03 ± 12.38 kg, stature = 178.94 ± 11.34 cm)	Force platform, 500 Hz, $P_i = F.v$	Jump and reach
Sayers et al. 1999 (CMJ and SJ)	59M (age = 21.3 ± 3.4 yrs, mass = 78.3 ± 15.4 kg) and 49F (age = 20.4 ± 2.2 yrs, mass = 64.7 ± 9.8 kg) college athletes and non-athletes	Force platform, 500 Hz – method not stated	Jump and reach
Shetty 2002 (CMJ)	19M untrained (age = 20.9 ± 1.3 yrs, mass = 78.9 ± 12.3 kg)	Force platform, 100 Hz, $P_i = F.$	Jump and reach
Canavan and Vescovi 2004 (CMJ)	20F college basketball players (age 20.1 ± 1.6 yrs, mass = 65.9 ± 8.9 kg)	Force platform, 500 Hz, method – Quattro Jump (Kistler)	Jump height determined by Quattro Jump – not defined
Lara et al. 2006	161M sports science students (age = 19 ± 2.9 yrs, mass = 70.4 ± 8.3 kg)	Force platform, 500 Hz, method – Quattro Jump (Kistler)	Jump height determined from flight time – method not stated

CMJ = countermovement jump,
SJ = squat jump,
f = sampling frequency,

Table 2.5 Summary of the methods of previous studies designed to develop regression equations to evaluate leg power from performance in a squat or countermovement jump

consequently, the validity of the regression equations is not clear. None of the studies reported the resolution of the analogue to digital converters that were used to convert the force platform's analogue voltage signal (proportional to the applied force) in to a digital signal nor were the force platforms' force ranges reported. Kibele (1998) used a 12 bit analogue to digital converter and considered that the errors associated with this level of resolution would have no effect on the values of force, velocity or displacement determined from the converter. However, no evidence was presented in support of this assertion and the range of the force platform used for testing was not reported.

Harman et al. (1991) recommended that the predictor jump should be performed from the force platform in order that the jump height could be estimated from the same jump used to derive the criterion measure of vertical mechanical power. Johnson and Bahamonde (1996) provided no information on jump simultaneity; however all remaining studies (Sayers et al. 1999; Shetty2002, Canavan and Vescovi 2003; Lara et al. 2006) used simultaneous jumps in their methods.

The measurement of mechanical power in a vertical countermovement jump is usually regarded as a measure of leg power. However, performance in a countermovement jump will be affected by the type of countermovement jump. Countermovement jumps are commonly performed in two ways, with and without arm swings. A vertical jump performed with arm swing has been reported to enhance jump performance (Lees et al. 2004). Consequently, if the purpose of a study is to produce a regression equation to estimate leg power from performance in a vertical jump, then it is important to minimise the influence of the arms. Arm swing was allowed in Johnson and Bahamonde (1996) and Shetty's (2002) jumps while Sayers et al. (1999)

	Author/s					
	Harman et al. 1991 (SJ)	Johnson and Bahamonde 1996 (CMJ)	Sayers et al. 1999 (CMJ)	Shetty 2002 (CMJ)	Canavan and Vescovi 2003 (CMJ)	Lara et al. 2006 (CMJ)
Method of integration	No info.	No info.	No info.	No info.	No info.	No info.
Sampling frequency (Hz)	500	500	500	100	500	500
Resolution of A to D converter	12 bits	No info.	No info.	No info.	No info.	No info.
Frequency of integration	20 Hz	No info.	No info.	No info.	No info.	No info.
Definition of time of the start of jump	No info.	No info.	No info.	No info.	No info.	No info.
Simultaneity of jumps[1]	No	No info.	Yes	Yes	Yes	Yes
Jump with arms immobilised	No	No	No info.	No	Yes	Yes
Definition of jump height (predictor)	Yes (h_j)[2]	No	Yes (h_j)	No	No	No (h_2)

1. This row states whether criterion method jumps and predictor jumps were carried out simultaneously.
2. h_j and h_2 are defined in Table 2.1

Table 2.6 Vertical jump parameters, variables and definitions needed to measure and estimate power and their inclusion or omission in previous regression studies

gave no information on whether arm swing was allowed in their jumps. Consequently the proportion of power produced in these jumps that can be accounted for solely by the legs is unclear as is the validity of both the criterion measure and the predictor measure. Both Canavan and Vescovi (2003) and Lara et al. (2006) immobilised the jumpers' arms by requiring them to place their hands on their hips (arms akimbo) throughout the jump thus isolating the legs, as far as possible, as the producer of power.

In all of the previous regression studies jump height has been a main predictor variable. It is common to define jump height in two different ways (Schwieger and Baca 2002) depending on the equipment that is available to measure this variable. The two definitions of jump height are illustrated in Figure 2.1 and are termed h_j and h_2. Clearly it is important to use the same definition and method of measuring jump height if a regression equation is to be used to estimate the vertical mechanical power output in a countermovement jump. However, Johnson and Bahamonde (1996), Shetty (1999) and Canavan and Vescovi (2003) do not define their jump heights; it is therefore unclear what definition, and method, of jump height measurement should be employed by future investigators wishing to use their regression equations. Lara et al. (2006) define jump height as being determined from flight time which, in turn, was determined from the Quattro Jump (Kistler, Switzerland.) system. No method of determining jump height from flight time was reported nor was a definition of flight time provided. Without this information, the validity of the jump height is unclear, and, consequently the validity their regression equation is also unclear. Sayers et al. (1999) clearly define jump height as h_j, determined from a jump and reach test. Standing reach height was determined with the subject's feet flat on the floor by reaching up as high as possible and placing a Velcro marker, from the tip of their middle finger, on a suitable board. The jump was then performed, with another Velcro marker mounted on the tip of their middle finger, and at the peak of the jump the marker was placed on the same board. The difference in the height of the two markers was a measure of h_j. If a future investigator wished to use their regression equation it would be straightforward to replicate Sayers et al.'s methods.

Canavan and Vescovi (2003) acknowledged that the number of subjects that they used, n = 20, was a limitation in their study. They recommended that on the basis of statistical power analysis and effect size the minimum number of subjects for this type of study should be 25. However of all the studies reported in Table 2.4, the regression equation of Canavan and Vescovi (2003) produced the highest agreement between criterion and predicted results; the percentage difference of the means was less than 1%, $R^2 = 0.92$ ($p<0.05$) with a standard error of the estimate (SEE) of 120.8 W. The small value of the SEE obtained by Canavan and Vescovi was attributed in part to their use of a homogeneous group of subjects (recreationally trained female basketball players with at least 3 years organised basketball experience). On the basis of Canavan and Viscovi's recommendation of a minimum sample size of 25, Shetty's (2002) sample size of 19 subjects, could be considered a limitation. Johnson and Bahamonde (1996) used 108 subjects with a percentage difference in the means of less than 1%, $R^2 = 0.91$ and a standard error of 462 W. Sayers et al. (1999) used 108 heterogeneous subjects and achieved a "standard error" of 561.5 W with a R^2 value of 0.78; no mean values were reported. Lara et al. (2006) used the largest group of subjects, 161 male sports science students, and achieved a percentage difference in means of 2.8%, which was not significantly different ($p<0.05$). Their SEE was 246.5 W which was twice that of Canavan and Vescovi's (2003). The larger SEE of Lara et al.'s results was attributed to the heterogeneity of their group compared to Canavan and Vescovi's.

Chapter 3

Method

3.1 Introduction

Section 2.6.2 highlighted the questionable validity of all the published regression equations for predicting human power output from performance in a countermovement vertical jump. Consequently, there would appear to be no valid regression equations for any population for predicting power output from field measures. Furthermore, there would appear to be no standard protocol for the measurement of power output in a countermovement jump by the criterion method, i.e. the product of force and velocity, obtained from a force-time recording of the jump. Consequently, the methodology of this study consists of three phases:

(i) Establishment of a clear protocol for the measurement of power output in a countermovement jump by the criterion force platform method.

(ii) Using the protocol to measure the power output of a group of young elite male rugby players.

(iii) Determination of a regression equation for predicting power output from field measures for this population.

3.2 Protocol for the measurement of power output in a countermovement jump by the criterion force platform method

In order to establish a clear, universally-applicable test protocol, it is necessary to define / describe the following variables: vertical range of the force platform, selection of sampling frequency, identification of the initiation of the countermovement jump, determination of body weight and force trace analysis. Finally these variables will be formed into a criterion method specification.

Prior to any testing with the force platform calibration checks were performed with calibration weight that were traceable to national standards.

3.2.1 Selection of a vertical force range

Accurate determination of the mechanical vertical power of a countermovement jump depends primarily upon an accurate force-time history of the countermovement jump. Before any physical quantity can be measured, it is necessary to know what the maximum value of that quantity is likely to be; in this case, the maximum vertical force. However, as a force platform measures vertical force as the arithmetic sum of four individual force transducers, one in each corner of the platform, it is also necessary to determine the maximum force to be measured by these individual force transducers. The vertical force measured by each of the four transducers in a countermovement jump will be different unless the applied force is in the exact geometrical centre of the force platform and consists only of a vertical component. This is illustrated in Figure 3.1 which shows the vertical ground

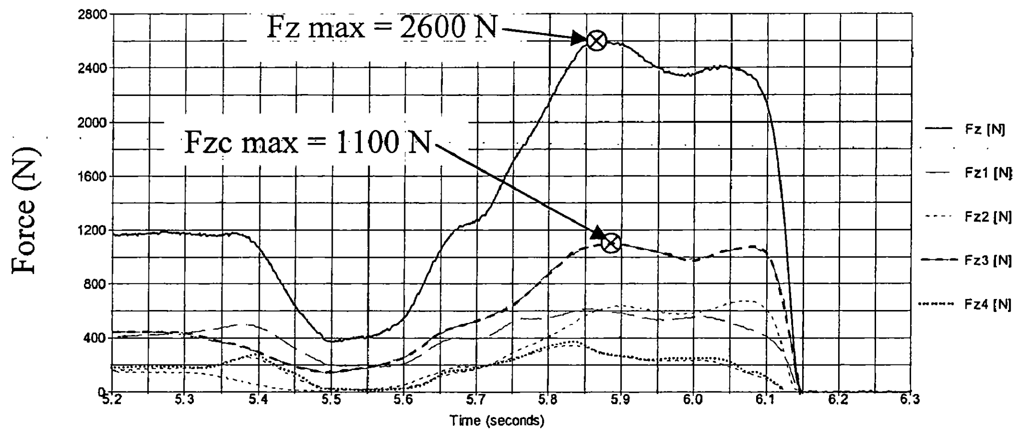


Figure 3.1 Vertical force-time history of a countermovement jump showing the four corner vertical force components.
Fz = resultant vertical force
Fz1 to Fz4 are corner vertical force components or generally Fzc

reaction force-time history of a countermovement jump and the four vertical components, corner force signals, that sum to give the total vertical force. The maximum vertical ground reaction force is 2600 N, however, the maximum vertical component ground reaction force (Fzc max) is 1100 N, almost half of the total vertical force.

To determine the maximum resultant vertical load and maximum component vertical loads that would need to be recorded when testing elite rugby players a pilot study was undertaken. Fifteen international rugby players, eight forwards and seven backs, (mass = 102.5 ± 12.3 kg), each performed a maximal countermovement jump. A Kistler force platform (9286AA) with an integrated charge amplifier was used to measure the ground reaction force. The analogue signals from the force platform were sampled at a frequency of 1000 Hz and interfaced to a data recording computer via a 16 bit analogue to digital converter. The measurement range of the system was set to 20 kN (ie 5 kN per corner transducer). Ground reaction force-time histories were recorded for each countermovement jump and the absolute maximum and minimum, total vertical force and the vertical component maximum and minimum forces were determined by inspection (Appendix D). Each subject's body weight was also determined from a portion of the graph, prior to the jump, when the subject was instructed to stand completely still. Table 3.1 shows the results of the pilot study.

	Fz max (N)	Fzc max (N)	Body weight (N)
Minimum	2060	770	799
Maximum	2950	1210	1166
Mean	2458	988	1005
Standard deviation	260	145	121

Table 3.1 Vertical forces produced during a countermovement jump

Fz max = maximum resultant vertical ground reaction force
Fzc max = maximum of the four corner component vertical forces

The maximum resultant vertical ground reaction force recorded in all trials was 2950 N in a jump by a subject with a body weight of 1166 N. This is consistent with Kibele (1998) who reported that maximum vertical ground reaction forces during a countermovement jump were in the region of 3 to 3.5 times body weight. However Kibele (1998) did not report component vertical loads. Not considering component loads can lead to errors due to the range of individual force transducers being exceeded. If, for example, the total vertical force range in the pilot study had been set on the basis of 3.5 times the body weight of the highest weight subject (1166 N), this would give a maximum expected vertical force of 4081 N, i.e. 3.5 times 1166 N, corresponding to a maximum range of 1020 N (4081 N ÷ 4) for each component force transducer. This value would have been exceeded in one or more component force transducers in 47% of the jumps in the pilot study causing an erroneous force reading which would not be obvious from the resultant vertical force record.

A more robust method of specifying the maximum vertical ground reaction force is to determine the maximum value for the component transducers. This can be calculated empirically from the pilot data. The range for the present study was defined as the mean maximum vertical component force plus five standard deviations, 988 N + (145 N x 5) = 1713 N. The corresponding resultant maximum vertical force range for the force platform would then be 1713 N x 4 = 6852 N. A force platform's range set to this value, or higher, would reduce the probability of it being exceeded to $p < 1 \times 10^{-6}$.

3.2.2 Selection of sampling frequency

Section 2.6 reviewed existing studies of human power output based on performance in a countermovement vertical jump and the variables that affect the quality of velocity-time data, and consequently power-time data, derived from collecting and integrating force-time data. Kibele (1998) used a sampling frequency of 1000 Hz and reported that an error of 5 to 10 ms in the identification of the initiation of a jump would only produce an error of 0.1% in the determination of take-off velocity but did not indicate the mechanism causing the error. Hatze (1998) used a sampling frequency of 2000 Hz and reported that the error in the determination of take-off velocity would amount to no more than 0.41% due to the extremely small intervals used to determine the integral (0.5 ms) of the force-time history. Hatze (1998) also reported that an error in detecting the initiation of the jump of ± 2 ms was of little consequence since the value of the integrand at the start of the jump must equal zero. Both studies were also concerned with jump height determined from take-off velocity, and reported that error in the determination of the instant of take-off would have a greater effect on the velocity at take-off than an equivalent error in the determination of the initiation of a jump, as the rate of change of force is far greater at take-off than at the initiation of the jump. The determination of peak vertical mechanical power derived from a force-time history doesn't require the determination of velocity at take-off as the peak power occurs prior to this time. Consequently it is not clear whether 1000 Hz or 2000 Hz or a lower sampling frequency, is suitable for the determination of peak power.

To investigate the effect of sampling frequency on the determination of power output from performance in a countermovement vertical jump, a pilot study was undertaken. Ten international rugby union players, seven forwards and three backs, (mass = 105.5 ± 13.9 kg), each performed a maximal countermovement jump. A Kistler force platform (9286AA) with an integrated charge amplifier was used to measure the ground reaction force. The analogue signals from the force platform were sampled at a frequency of 1000 Hz and interfaced to a data recording computer via a 16 bit analogue to digital converter. The vertical measurement range of the system was set to 20 kN (ie 5 kN per component transducer). The force-time histories were then re-sampled and saved at 500 Hz and 100 Hz, thus producing force-time data for the same countermovement jumps at three different sampling frequencies: 100 Hz, 500 Hz and 1000 Hz. Peak mechanical vertical power was determined for each jump at the three sampling frequencies, using Simpson's rule at the corresponding frequency to determine the velocity-time data (Appendix E). Body weight was defined as mean ground reaction force during one second of the stationary stance phase prior to the initiation of the jump. The initiation of the jump was defined as the point when the vertical ground reaction force, after a signal to jump had been given, exceeded the mean ground reaction force of the stance phase (body weight) plus or minus five standard deviations of the mean value. As the same method (incorporating the determination of body weight, initiation of jump and Simpson's rule) was used to determine vertical mechanical power of all jumps, differences in peak power for each jump could be attributed to the different sampling frequencies. To determine the limits of agreement and mean differences of power output produced by the 100 Hz and 500 Hz sampling frequencies, in relation to the power outputs of the1000 Hz sampling frequency, Bland and Altman (1986) plots were used. The results obtained from the force-time data sampled at 1000 Hz were assumed to be more accurate than the results obtained from the 100 Hz and 500 Hz force-time data. Therefore the differences between the results obtained for the 100 Hz and 500 Hz data were compared to the results obtained from the 1000 Hz data. The results of the pilot study can be seen in Figures 3.2a and 3.2b.

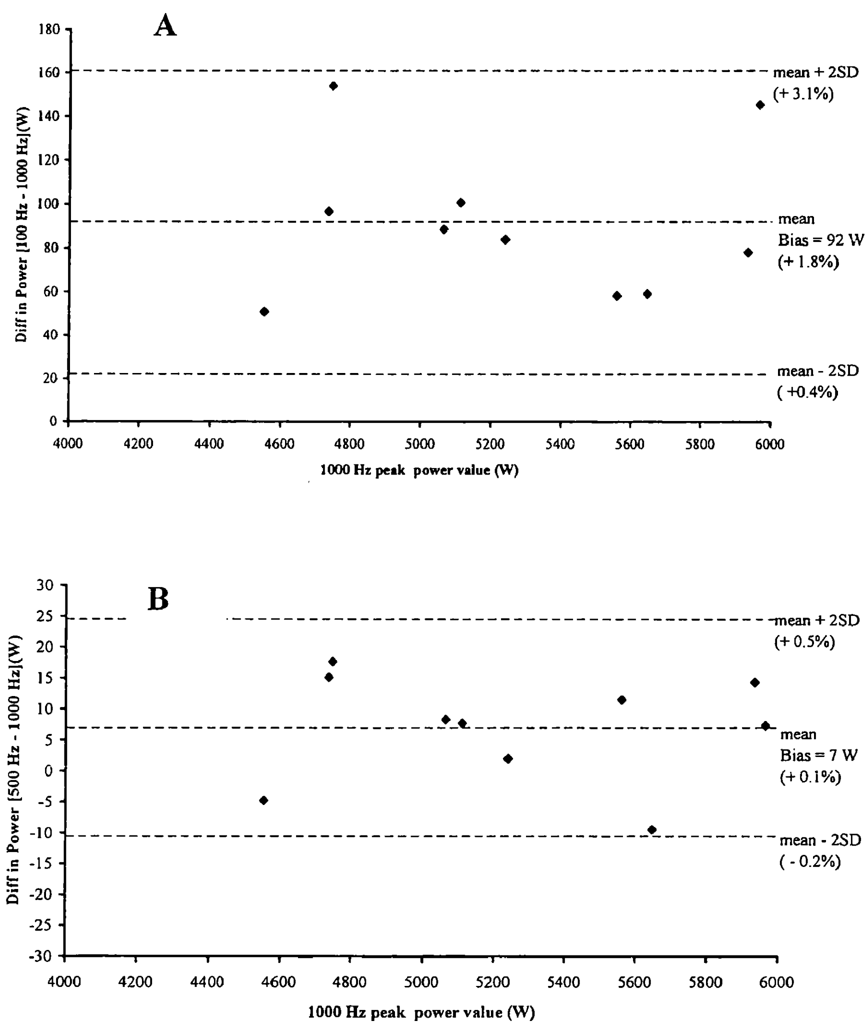


Figure 3.2a Bland and Altman plot comparing peak vertical mechanical power outputs of countermovement jumps using sampling frequencies of 100 and 1000 Hz. And 3.2b Bland and Altman plot comparing peak vertical mechanical power outputs of countermovement jumps using sampling frequencies of 500 and 1000 Hz.

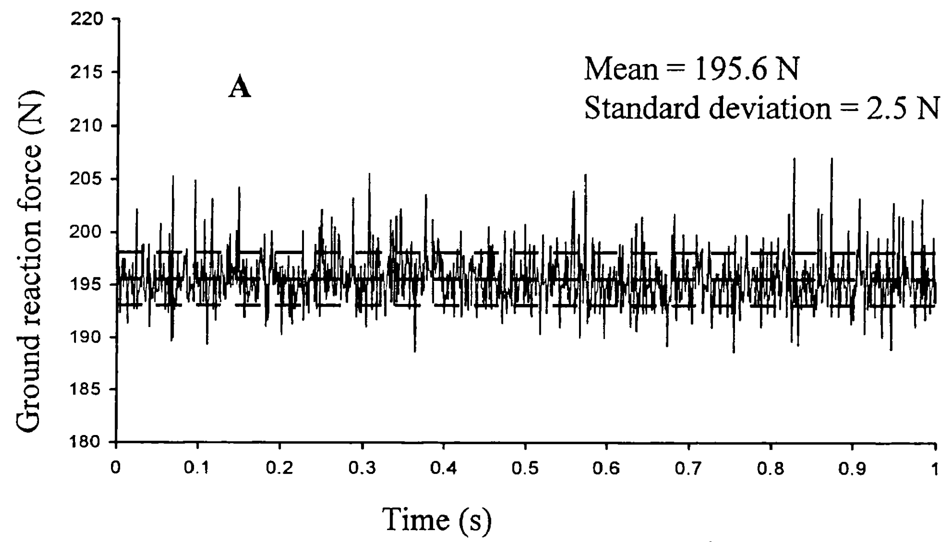
The sampling frequency of 100 Hz, when compared to 1000 Hz produced a mean difference of 2.8% and limits of agreement (mean ± two standard deviations) of +3.1% and + 0.4%. The sampling frequency of 500 Hz, when compared to 1000 Hz produced a mean difference of +0.1% with limits of agreement +0.5% and -0.2%. It can be reasonably assumed that the mean difference and limits of agreement between a 1000 Hz sampling frequency and a 2000 Hz sampling frequency would be at least as good as, or better than, those obtained for the comparison between 500 Hz and 1000 Hz. This being the case, there would be no need to sample at 2000 Hz as a sampling frequency of 1000 Hz would achieve precision of less than 1%. It is also highly likely that 500 Hz would also achieve this precision. The worst case scenario for the precision of a sampling frequency of 500 Hz would be that the mean difference and limits of agreement of 1000 Hz sampling frequency compared to 2000 Hz sampling frequency were the same as for 500 Hz compared to 1000 Hz giving a mean difference between 500 Hz and 2000 Hz of +0.2 % with an upper limit of agreement of +1.0 % and a lower limit of agreement of -0.4%. However, as a sampling frequency of 1000 Hz was shown to produce more accurate results for peak power than a sampling frequency of 500 Hz, and the convenience of sampling in time intervals of milliseconds, a sampling frequency of 1000 Hz was chosen as the preferred frequency for the determination of power output by the criterion force platform method in this study.

3.2.3 Determination of body weight

Methods of determining body weight from a force-time record were discussed in Section 2.6 and for reasons described in that section, body weight was determined by taking the mean ground reaction force value, as measured by the force platform, for one second of the stance phase immediately prior to the signal to jump being given. In the pilot study, sampling frequency (100 Hz, 500 Hz and 1000 Hz) had an insignificant effect on the determination of body weight using this method.

3.2.4 Identification of the initiation of a countermovement jump

A countermovement jump consists of two distinct phases; the stationary phase and the jump phase. The stationary phase is necessary for the evaluation of body weight and starts when the subject adopts a stationary, upright position on the force platform prior to the start of the jump phase. The stationary phase ends when the jump starts. With respect to the sampling frequency of the ground reaction force, the initiation of the jump phase corresponds to the sample immediately prior to the start of movement. The identification of this instant is important as it also serves as the starting point for integration and, as such, the condition that the vertical velocity of the whole body centre of gravity must equal zero needs to be met. Consequently it would therefore seem reasonable to define the jump initiation as the instant when the ground reaction force no longer equalled body weight. However the vertical component of the ground reaction force will vary constantly due to slight movement of the subject (it is not possible for a human subject to stand perfectly still) and noise in the instrumentation. Consequently, body weight must be represented by a mean value with an associated uncertainty, usually reported as the standard deviation. Figure 3.3 A shows the variation in the measurement of the weight of a 20 kg calibration mass and Figure 3.3 B shows the variation in the measurement of the body weight of a subject, both at rest on a force platform.



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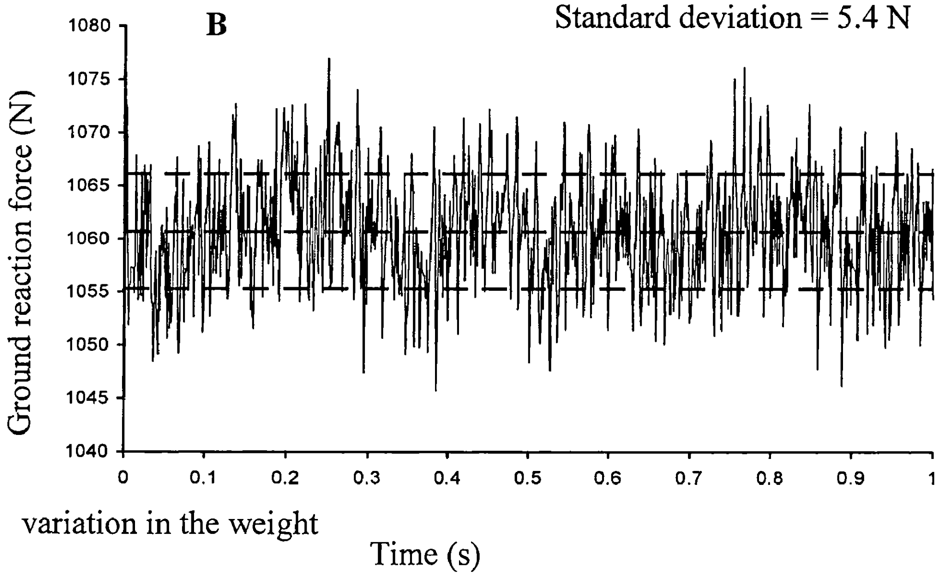


variation in the weight

of

Figure 3.3A Force-time history of a 20 kg calibration mass and 3.3B force-time history of a subject during the stance phase of a countermovement jump. The mean ground reaction force and ± 1 standard deviation values are represented by dashed lines.

the calibration mass is solely due to system noise, whereas the variation in the weight of the subject standing still is due to both the system noise and slight vertical oscillation of the whole body centre of gravity due to breathing and pendular sway of the whole body centre of gravity over the feet in order to actively maintain balance. The weight of the calibration mass was measured as 195.6 ± 2.5 N and the weight of the subject in the stance phase was measured as 1060.7 ± 5.4 N. In order to identify when the body weight of a subject has changed beyond the normal variation, a threshold level of normal variation needs to be established. If the threshold variation was set at mean body weight plus or minus three standard deviations, then 99.7% of all values would lie within this range. However if ground reaction force-time histories in excess of one second need to be analysed then, as a one second sample contains 1000 force values and the probability of a value lying outside the range is, $p = 0.003$, it is probable that this limit would be exceeded three times in a second for the stationary stance phase, thus giving an erroneous initiation. Similarly if the threshold variation was set at mean body weight plus or minus four standard deviations, the probability of this range being exceeded would be reduced to, $p = 0.00006$ or one erroneous initiation for every ten trials, which would be unacceptable. Setting the threshold variation at mean body weight plus or minus five standard deviations would reduce the probability of an erroneous initiation to, $p = 0.000000002$. If a one second stance phase was analysed for each trial, this would correspond to one erroneous initiation for every thousand trials. It therefore seems reasonable to define the initiation time, t_s, as the instant, after the signal to jump has been given, that the ground reaction force value exceeds the mean plus or minus five standard deviations of the body weight as measured in the stationary stance phase.

To investigate the effect of varying t_s, and consequently its suitability as a start point for measuring instantaneous power, a pilot study, using the pilot study data from Section 3.2.2, was undertaken. Time, t_s, was identified for the ten force-time histories. Instantaneous power was then determined using an integration starting point equal to, t_s – 100 ms, for each subject. The point t_s - 100 ms was chosen as it was clearly in the stationary stance phase of the jump; this is illustrated in Figure 3.4. Values of instantaneous power were determined at t_s -40 ms through t_s, to t_s + 30 ms at intervals of 10 ms (Appendix F). Integration started in the stationary phase of the jump (t_s – 100 ms), therefore the value of instantaneous power at any subsequent point, would represent a deficit if integration had been started at that point as vertical velocity, and hence power, is taken as zero at the initiation of the jump. Figure 3.5 shows the results of the pilot study, the mean power and error bars of plus and minus three standard deviations. The mean powers, determined at points t_s – 40 ms through to t_s -30 ms (in 10 ms steps), varied from -2 W to + 1 W. At the initiation of a countermovement jump, movement of the whole body centre of gravity is equally likely to be upwards as it is downwards and as upward movement would produce a positive value of power and downward movement a negative value of power, these power values would cancel each other out thus accounting for the very small variation in mean power between different starting points. However the standard deviation can be seen to rise rapidly after t_s, indicating an increasing variation in power after point t_s. The variation in power at a particular start point, as compared to $t_s - 100$ms, of a countermovement jump can reasonably be considered as an error as it is power that would not be accounted for if integration had been started at that point. To determine the possible effect of starting point error it is necessary to consider the effect that this error would have on determining peak power. It is reasonable to expect the maximum variation in power, due to different starting points, to fall within the range of mean power plus or minus three standard deviations ($p<0.005$). However as power is the product of velocity and force and as peak force during a countermovement jump does not exceed 3.5 times body weight (Kibele 1998), it is reasonable to expect that the maximum variation in peak power should be no greater that 3.5 times the maximum expected variation of power at the initiation of a jump i.e. three standard deviations. Tables 3.2 shows the expected maximum variation in peak power corresponding to different jump initiation times. Jump initiation times of t_s – 40 ms, t_s -30 ms, t_s – 20 ms and t_s -10 ms produced the lowest expected uncertainty, ± 0.5%, in peak power values. It is likely that uncertainties of this magnitude are due to noise in the force signal and inability of human subjects to stand perfectly stationary during the stance phase. As the expected uncertainty in peak power starts to increase at t_s, it is reasonable to assume that the jump has already started at this point.

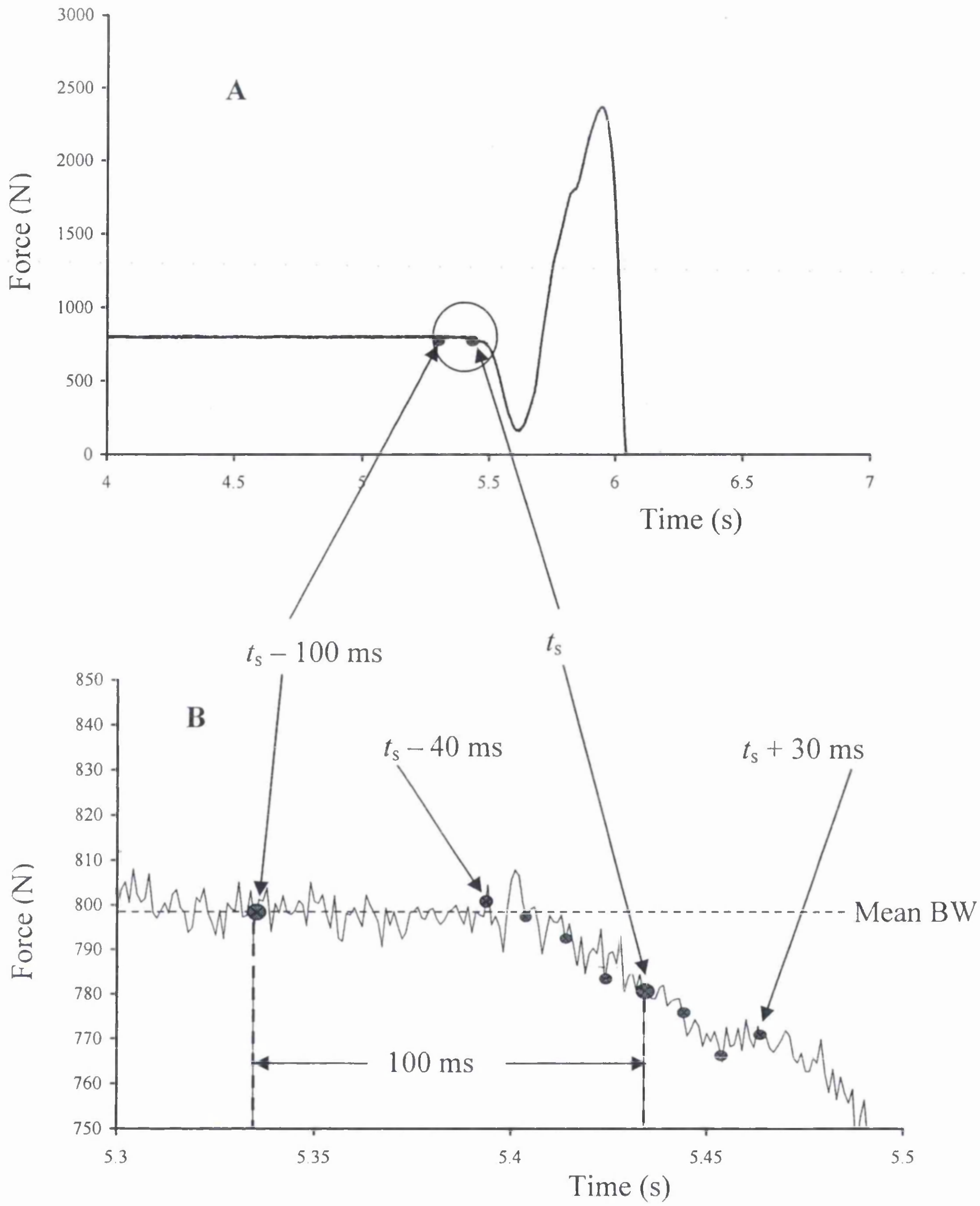


Figure 3.4a A typical force-time history of a countermovement jump, and preceding stationary stance phase, with t_s (initiation of jump) and $t_s - 100$ ms indicated. 3.4b shows an enlargement of the circled section of Figure 3.2a with t_s and $t_s - 100$ ms also indicated. The pilot start points, of t_s - 40 ms through to $t_s + 30$ ms at intervals of 10 ms, are indicated as the smaller markers

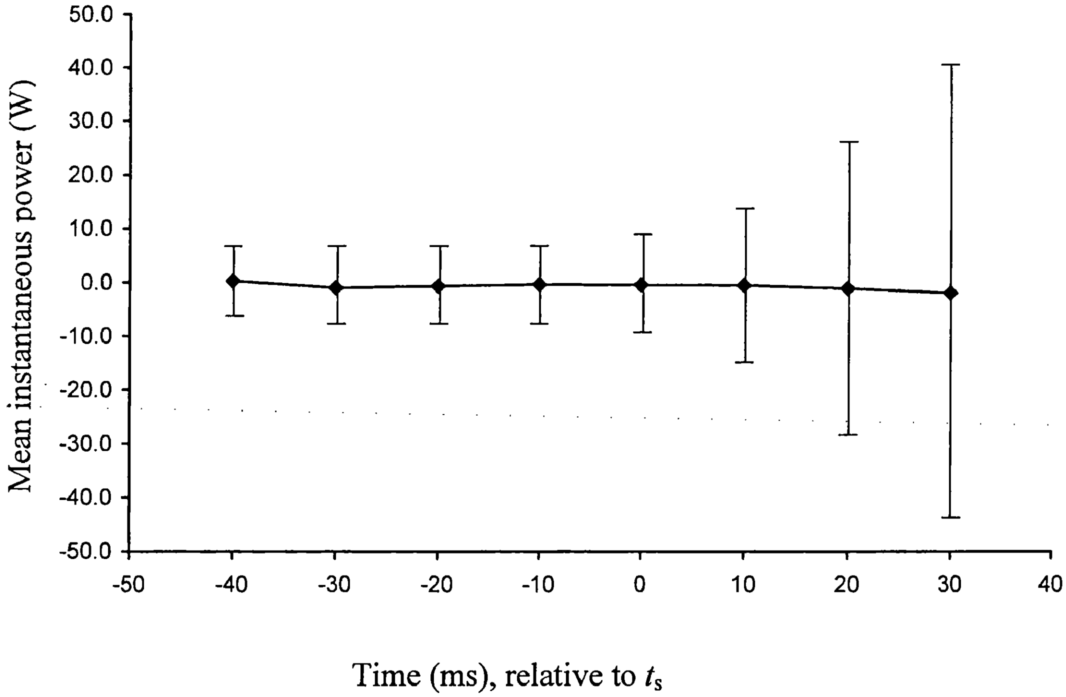


Figure 3.5 Results of pilot study to determine the effect of varying the initiation time of a jump. The graph shows the mean instantaneous power and error bars of ± 3 standard deviations, measured at t_s -40 ms to t_s + 30 ms, integration was started at t_s- 100 ms,

	Jump initiation time relative to t_s (ms)							
	-40	-30	-20	-10	0	+10	+20	+30
% maximum variation in peak power ($p<0.005$)	±0.5	±0.5	±0.5	±0.5	±0.6	±1.0	±1.8	±2.8

Table 3.2 Percentage uncertainty expected in peak power as a result of varying the jump initiation time.

It can therefore be concluded that the jump starts somewhere between t_s-10 ms and t_s and as such t_s-10 ms, can be identified as the jump initiation.

The preferred jump initiation, t_i, for the determination of power output by the criterion force platform method in this study was defined as, $t_s - 10$ ms, where $t_s =$ the instant, after the signal to jump has been given, that the ground reaction force exceeded body weight plus or minus five standard deviations.

3.2.5 Method of numerical integration

In order to determine the power-time history of the performance of a subject in a countermovement jump, it is necessary to numerically integrate the resultant vertical force-time history. Power is then determined from the product of the force and velocity. The two most common methods of numerical integration use the trapezoidal rule and Simpson's rule. Kibele (1998) and Vanrenterghem (2001) both used the trapezoidal rule. Some biomechanical analysis software, such as Kistler Bioware (Kistler instruments 2005) uses Simpson's rule. Kibele (1998) reported that if sampling frequencies are high (1000 Hz in his case), then the use of higher order integration methods, such as Simpson's rule, would not significantly improve the precision of integration. A sampled force-time history is composed of force values recorded at discrete time intervals, these force points are joined, by straight lines, to form a graph which represents the actual force-time history. The area under a sampled force-time history therefore consists of a series of consecutive trapezoids, each of width equal to the inverse of the sampling frequency and height represented by the value of the force recorded for the corresponding sample point. Therefore the use of the trapezoidal rule to determine the integral of a sampled force-time history will produce a perfectly accurate result. In contrast Simpson's rule approximates the sampled points of a force-time history to a curve. However it is not clear which method produces the most accurate integral of the actual force-time history.

To investigate the effect of the method of integration on the determination of power output from performance in a countermovement vertical jump, a pilot study was undertaken. Ten international rugby union players, seven forwards and three backs, (mass = 105.5 ± 13.9 kg), each performed a maximal countermovement jump. A Kistler force platform (9286AA) with an integrated charge amplifier was used to measure the ground reaction force. The analogue signals from the force platform were sampled at a frequency of 1000 Hz and interfaced to a data recording computer via a 16 bit analogue to digital converter. The vertical measurement range of the system was set to 20 kN (ie 5 kN per component transducer). Peak mechanical vertical power was determined for each jump, first using Simpson's rule and then using the trapezoidal rule at the sampling frequency to determine the velocity-time data (Appendix G). Body weight was defined as mean ground reaction force during one second of the stationary stance phase prior to the initiation of the jump. The initiation of the jump was defined as t_i (Section 3.2.4). To determine the limits of agreement and mean differences of peak power output produced by the two methods of numerical integration, Bland and Altman (1986) plots were used. As it was unclear which of the two methods of integration produced the more accurate result the best estimate of the actual peak power value was taken as the mean of the two measurements (Bland and Altman 1986). The results of the pilot study can be seen in Figure 3.6, the difference between peak powers calculated using Simpson's rule and the trapezoidal rule is plotted on the y axis and the mean peak power (mean between the Simpson's rule value and the trapezoidal rule value) is plotted on the x axis.

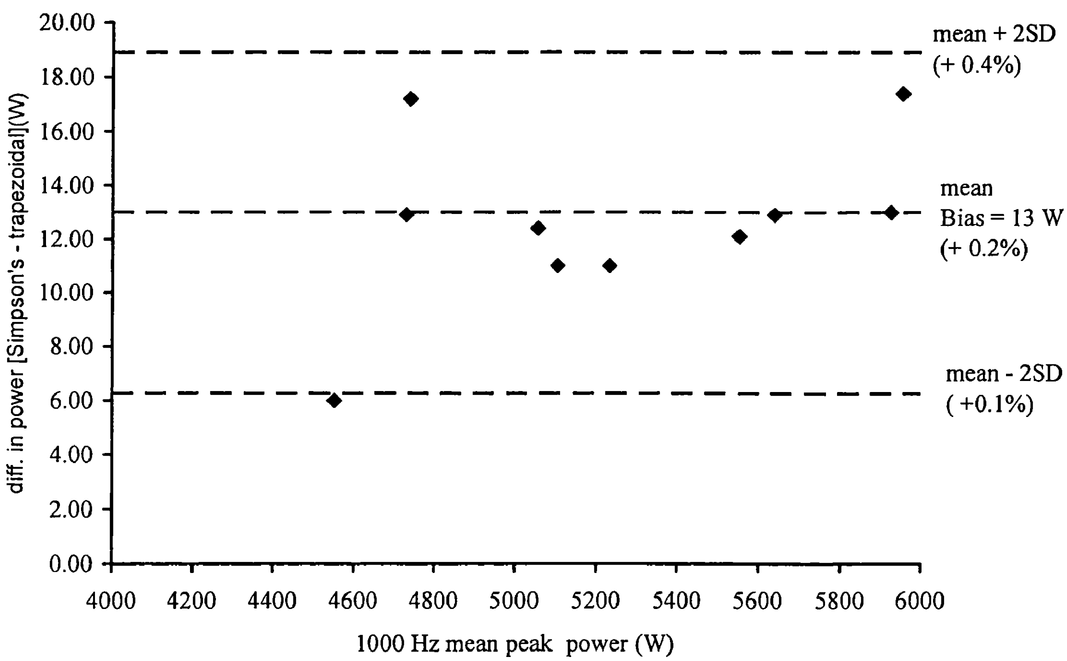


Figure 3.6 Bland and Altman (1996) plot illustrating the limits of agreement between Simpson's rule and the trapezoidal rule when used in the process of determining peak vertical mechanical power outputs of countermovement jumps.

The analysis resulted in a mean of the difference of 13 W (bias, +0.2%) and lower and upper limits of agreement (mean ± two standard deviations) of 6 W (+

0.1%) and 19 W (+ 0.4%) respectively. Thus the maximum error, ΔP, in the determination of peak power between Simpson's rule and the trapezoidal rule would be, $\Delta P \leq 0.4\%$ (C.I. = 95%). It can therefore be concluded that if a maximum error of 0.4 % in the determination of peak power is acceptable then the two methods of numerical integration, Simpson's rule and the Trapezoidal rule, can be used interchangeably.

For the current study Simpson's rule was used on the basis that Kistler's Bioware program (version 3.24) was more convenient to use than the custom program using the trapezoidal rule.

3.2.6 Criterion method specification

Sections 3.2.1 to 3.2.5 (inclusive) detailed the empirical analysis of all the variables necessary to define a reliable criterion method to determine the vertical mechanical power of the whole body centre of gravity of a subject performing a countermovement jump. The results of the investigations are summarised in Table 3.3.

Variable	**Criterion method specification**
Vertical force range and resolution	6852 N or higher at 16 bit resolution
Sample frequency	1000 Hz
Integration frequency	1000 Hz
Method of integration	Simpson's rule
Determination of body weight, BW.	Mean ground reaction force measured for one second of the stationary stance phase immediately prior to the signal to jump
Determination of initiation of jump, Ts.	(The instant that BW ± five standard deviations is exceeded after the signal to jump has been given) minus 10 ms

Table 3.3 Criterion method specification for the measurement of instantaneous power in a countermovement jump by the criterion force platform method.

3.3 Experimental protocols

The test protocol defined in section 3.2.6 was used to determine the peak vertical mechanical power of elite, under 21 year old male, rugby union players ($n = 59$, age = 19 ± 1 years, mass = 96.6 ± 11.7 kg, height = 1.860 ± 0.060 m).

3.3.1 Protocol for data collection

A portable Kistler force platform with built-in charge amplifier (type 92866AA, Kistler Instruments Ltd, Farnborough, UK) was used to measure the vertical ground reaction force of the subjects during performance of maximal effort countermovement jumps. A sample rate of 1000 Hz and a vertical force range of 20 kN (ie 5 kN per component transducer) was used for all jumps and the platform's calibration was confirmed pre and post testing. The force data was converted into digital signals by a 16 bit analogue to digital converter and force-time histories were recorded on a portable computer. The force platform system was equipped with a triggering switch to initiate data collection. The trigger switch that initiated data collection also simultaneously initiated a signal lamp used to inform the subject to perform a countermovement jump. Figure 3.7 shows a schematic diagram of the data collection apparatus.

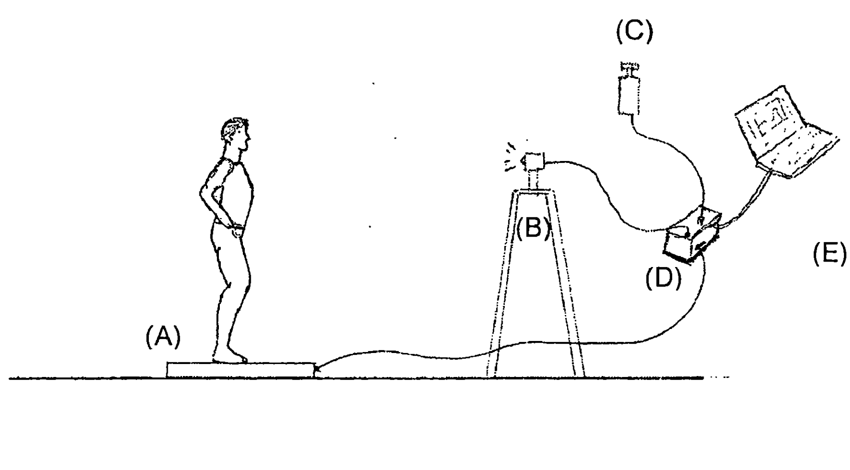


Figure 3.7. Schematic diagram of data collection apparatus showing a subject on the force platform (A), the visual signal (B), the trigger switch (C) the junction box (D) and the data collection computer (E).

A sample length of 5s was used for all jumps, consisting of a pre-trigger phase of duration 1 s, and a post-trigger phase of duration 4 s. The pre-trigger phase was a record of the force-time history immediately prior to the trigger switch being operated, and the post-trigger phase, which included the countermovement jump, was a record of the force-time history immediately after the trigger switch had been operated. The two phases were continuous, forming a single 5 s force-time. Figure 3.8 shows a sample 5 s force-time history of the vertical component of the ground reaction force in a countermovement jump with the pre-trigger phase, post-trigger phase and trigger point indicated.

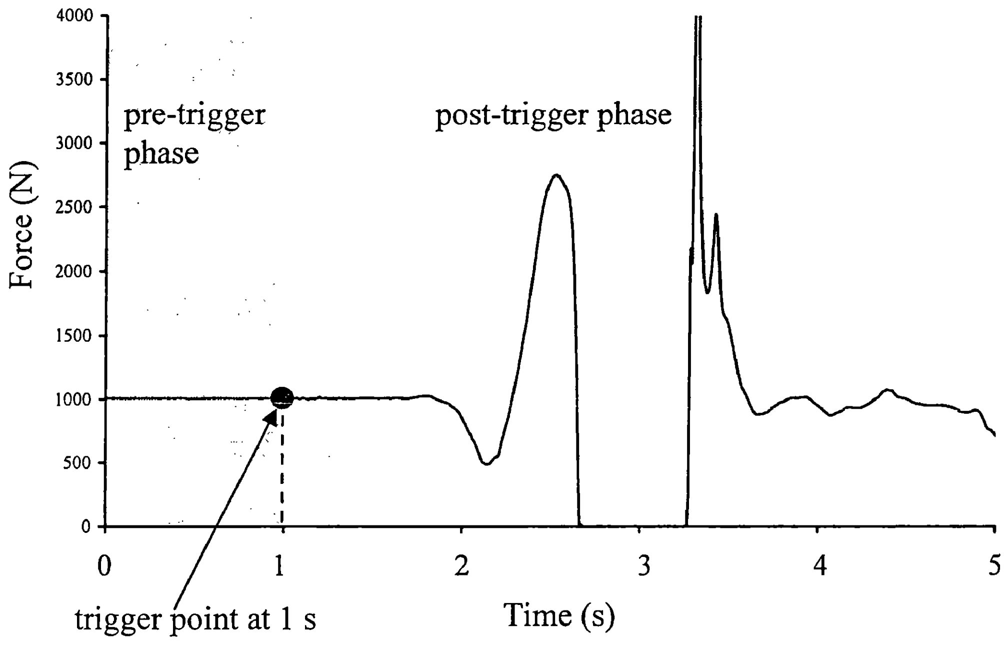


Figure 3.8 Typical vertical ground reaction force-time history of a countermovement jump showing the trigger point, pre-trigger phase and post-trigger phase.

After a prescribed warm up and sufficient rest, to avoid the effects of fatigue, each subject was asked to step on the force platform and place their hands on their hips. Then they were instructed to stand as still as they could, in an upright position, and wait for the lamp signal. In response to the lamp signal, the subject was required to perform a maximum-effort countermovement jump with the objective of jumping as high as possible, while keeping their hands on their hips. It was explained that the test was not a test of their reaction to the signal lamp, but they should jump as soon as it illuminated. When a subject had been visually judged to be stationary for a continuous period of about 2 s the trigger switch was activated. Thus it was ensured that the pre-trigger phase, i.e. the period of time between 0 s and 1 s of the 5 s sample, was a stationary phase and could be used to determine body weight.

Subjects were required to perform only one jump on the basis that countermovement jumps, performed in the same fashion but on a jump mat, formed part of their weekly testing regime. Subjects and coaches were confident that a maximal jump could be performed on the first attempt. If however any subject felt that they had under-performed then, after a rest of at least four minute, the subject repeated the jump. Only one subject asked to repeat the jump.

3.3.2 Protocol for data analysis

After data collection a number of procedures were necessary to determine peak instantaneous vertical mechanical power of the whole body centre of gravity in each jump. The first procedure was to determine body weight which was then used to determine the initiation of the jump. A copy of the vertical force-time record of the jump was exported from the data collection software (Kistler's Bioware version 3.24), to Microsoft Excel. A program written specifically for this study calculated the body weight of the subject by determining the mean vertical ground reaction force during the one second pre-trigger phase; see figure 3.9. Standard deviation of the body weight was also determined from the same data.

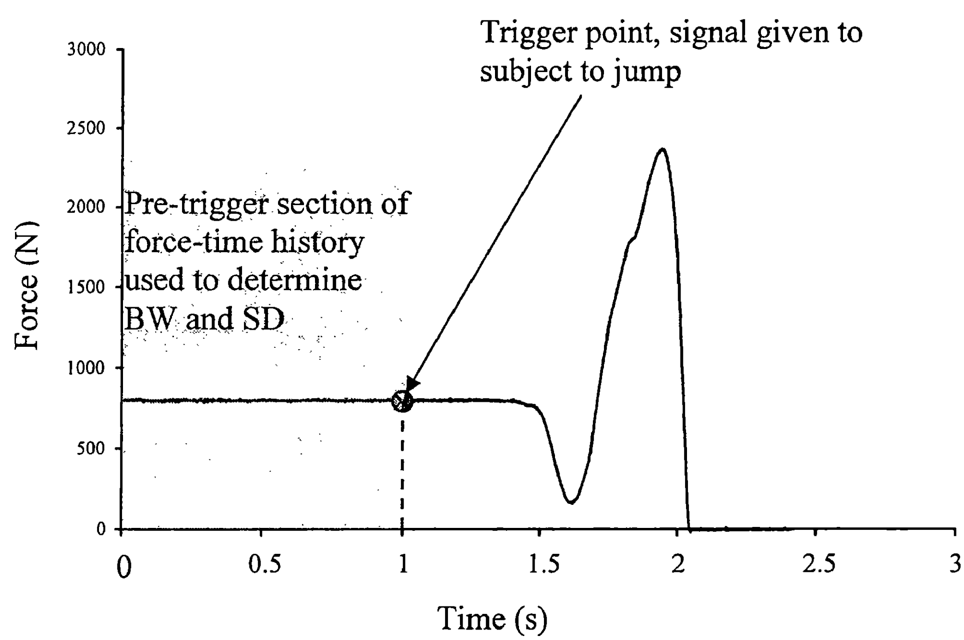


Figure 3.9 Vertical ground reaction force-time history showing trigger point and pre-trigger section used to determine body weight

The program then used these data to set the threshold values of body weight ± 5 standard deviations. The instant that the vertical ground reaction force exceeded the threshold values, t_s, was determined and from this value the jump initiation time, t_i was defined: $t_i = t_s - 10$ ms. Output from the program consisted of two variables, body weight and jump initiation time, t_i. All data before t_i and after take-off was discarded, as peak instantaneous vertical mechanical power occurs before take-off. The subject's body mass was determined by dividing the mean body weight (determined by the Excel program) by acceleration due to gravity ($g = 9.80665$ m.s^{-2}). The net resultant vertical force-time record was then integrated with respect to time from t_i to take-off with the constant of integration, v_{zti}, set to zero. Equation 1, section 2.4, and Simpson's rule was used for this procedure giving a result of instantaneous vertical velocity of the whole body centre of gravity.

$$v_{zt} = v_{zt_i} + \int_{t_i}^{t} \frac{F_z}{m} - g.dt \qquad \text{---------- (equation 1, section 2.4)}$$

Instantaneous vertical mechanical power, P_i, was then determined from t_i to take-off using equation 3, section 2.4.

$$P_t = F_{zt}.v_{zt} \quad \text{------- (equation 3, section 2.4)}$$

Peak positive instantaneous vertical mechanical power of the whole body centre of gravity between t_i and take-off was then recorded.

3.3.3 Determination of regression variables

The variables used in the regression analysis were jump height (m) [estimated from flight time] and body mass (kg). These variables were chosen as they can be measured easily and accurately within a field based setting.

3.3.3.1 Protocol for the estimation of jump height from flight time

An estimate of the height attained by the whole body centre of gravity, after take-off, during a countermovement jump (h_2, Figure 2.1) can be determined from the jump fight time. If the whole body centre of gravity remains in the same position for take-off and landing then an estimate of h_2 is given by, $h_2 = \frac{1}{8}.g.T^2$ where T = flight time (s) and g = acceleration due to gravity ($m.s^{-2}$), (Kibele, 1998). To estimate flight time in a field setting a jump mat can be used as it is relatively cheap, accurate and reliable (Szmuchrowski et al. 2007). Jump mats operate on the principle that when a subject stands on the mat a resulting condition exists that prevents a timing device from operating. When the subject leaves the mat, on take-off, a resulting condition exists that allows the timing device to start timing. When the subject lands back on the mat the resulting condition stops the timing device, thus the timing device records the duration of the flight phase of a jump.

For this study the duration of the flight phase of a countermovement jump was determined from the vertical force-time history thus providing a measure of flight time of the jump. The force-time history was resampled at a frequency of 100 Hz, the most common frequency of operation of jump mats. The time of take-off was defined as the time, after jump initiation, of the first sample point after the vertical force had dropped below 5 N, and the time of landing was defined as the time, after take-off, of the last sample before the vertical force exceeded 5 N. Flight time, T, was then define as, T = landing time (s) – take-off time (s).

3.3.3.2 Determination of body mass

Body mass was derived from body weight determined during the stationary phase of the countermovement jump. Body mass was defined as body weight (N) ÷ 9.80665 ($m.s^{-2}$).

3.3.4 Statistical methods

Descriptive statistics, mean and standard deviation, were determined for the subjects' ages (years), body masses (kg), body weights (N), heights (m), peak vertical mechanical powers (W)[determined using the criterion method] and jump heights (m)[S_{ft}, estimated from flight times derived from 100 Hz force-time histories].

3.3.4.1 Multiple regression analysis

Simple multiple regression was performed (SPSS, Illinois) with absolute peak vertical mechanical power as the outcome variable and body mass and jump height (S_{ft}) as the significant predictor variables. The predictor variables were both included in the regression using the enter method. Nineteen subjects were chosen at random and withheld from the determination of the regression equation as a cross validation group. The remaining 40 subjects were used to determine a regression equation. The regression equation was then used to predict the peak vertical mechanical power of the 19 subjects of the cross validation group. t tests were then used to determine if there was a significant difference ($p \leq 0.05$) between the predicted and the criterion measures of peak mechanical vertical power of the cross validation group. If there was no significant difference between the criterion and predicted measures of peak mechanical vertical power in the cross validation group, the two groups were combined and a multiple regression equation was determined from the combined group of 59 subjects.

3.3.4.2 Linear regression analysis

Linear regression was performed (SPSS, Illinois) with relative peak vertical mechanical power (normalised to body weight) as the outcome variable and jump height (S_{ft}) as the predictor variable. Nineteen subjects were chosen at random and withheld from the determination of the linear regression equation as a cross validation group. The remaining 40 subjects were used to determine a linear regression equation. The regression equation was then used to predict the relative peak vertical mechanical power of the 19 subjects of the cross validation group. t tests were then used to determine if there was a significant difference ($p \leq 0.05$) between the predicted and the criterion measures of relative peak mechanical vertical power of the cross validation group. If there was no significant difference between the criterion and predicted measures of relative peak mechanical vertical power in the cross validation group, the two groups were combined and a linear regression equation was determined from the combined group of 59 subjects. The resulting linear regression equation was in the form:

Estimated relative peak power ($W.N^{-1}$) = $(M \,.\, S_{ft}) + C$ - - - - - - - - - 3.1

Where S_{ft} = jump height estimate (m), M = the predictor coefficient (slope of the regression line) and C = constant

To determine the absolute peak vertical mechanical power for a subject from equation 3.1 both sides of the equation were multiplied by the subject's body weight resulting in equation 3.2.

Estimated absolute peak power (W) = BW x $(((M \,.\, S_{ft}) + C))$ - - - - - - 3.2

Where BW = body weight (N), S_{ft} = jump height estimate (m), M = the predictor coefficient (slope of the regression line) and C = constant.

Chapter 4

Results

4.1	Results of criterion measure of instantaneous vertical mechanical power of the whole body centre of gravity and jump height estimators
4.2	Results of multivariate regression using absolute peak power as the outcome variable
4.3	Results of linear regression using relative peak power as the outcome variable
4.4	Comparison of the results from the absolute and relative regression equations

4.1 Results of criterion measure of instantaneous vertical mechanical power of the whole body centre of gravity and jump height estimators

Peak instantaneous vertical mechanical power of the whole body centre of gravity for countermovement jumps, jump heights and body weights were measured and body masses determined, using protocols described in chapter 3, for elite under 21 year old male, rugby union players ($n = 59$, age = 19 ± 1 years, mass = 96.6 ± 11.7 kg, height = 1.860 ± 0.060 m). The results are recorded in Appendix H. The mean peak power output was 5257 ± 728 W, with a range of 3647 W to 6796 W. The mean jump height (S_{ft}, estimated from flight times derived from 100 Hz force-time histories) was 0.381 ± 0.059 m, with a range of 0.259 m – 0.550 m. Mean body weight was 947 ± 115 N, with a range of 708 N to 1125 N.

4.2 Results of multivariate regression using absolute peak power as the outcome variable

Table 4.2 shows that correlations (Pearson r) between the predictor and outcome variables were low but highly significant ($p < 0.002$). Power output correlates positively with jump height and mass with correlation coefficients of $r = 0.411$ and $r = 0.480$ respectively. Mass and jump height correlate negatively with a correlation coefficient of $r = -0.416$. Scatter graphs of these relationships are shown in Figure 4.1. Multiple regression (SPSS, Illinois) was used to predict peak vertical mechanical power (Pp_{est1} (W)) of the whole body centre of gravity

	Peak power	Jump height	mass
Peak power	1	0.411	0.480
Jump height	0.411	1	-0.416
mass	0.480	-0.416	1

Table 4.1 Correlation matrix (Pearson r) for predictor and outcome variables. Significance level for all correlation coefficients is $p < 0.002$

from jump height (S_{ft} (m)) estimated from flight time and body mass (M (kg)). The equation resulting from the regression analysis was:

$$Pp_{est.}(W) = [9026.19 \times S_{ft}\,(m)] + [48.96 \times M\,(kg)] - 2910.9 \quad \text{--------} \quad 4.1$$

The regression equation accounted for 68.1% of the variation in power ($R^2 = 0.681$, $p<0.001$) and had a standard error of the estimate (S.E.E.) of 412 W. Figure 4.2 shows a scatter graph of estimated peak power, determined using the regression equation, and actual peak power and a Bland and Altman plot (Bland and Altman 1986) for these data. The mean peak power (actual) was 5257 W, the mean bias of the estimated peak power was insignificant, 2 W, and the standard deviation of the differences was 412 W giving limits of agreement (LOA) of + 810 W (15.4 %) and - 806 W (15.4 %), p = 0.05. These results are summarised in Table 4.3.

Regression equation	$Pp_{est1}(W) = [9026.19 \times S_{ft} (m)] + [48.96 \times M (kg)] - 2910.9$
Regression statistics	$R^2 = 0.681$, $p < 0.001$, S.E.E. = 412 W (7.8% of mean)
Bland and Altman statistics	Bias = 2 W, limits of agreement are +810 W and -806 W (± 15.4 % of mean), p = 0.05

Table 4.2 Regression equation for estimating peak vertical mechanical power of the whole body centre of gravity for a countermovement jump and regression and Bland and Altman statistics.
Pp_{est1} = peak power estimated from jump height and body mass, S_{ft} = jump height estimate determined from flight time, M = body mass of subject.

A complete list of all peak powers estimated using equation 4.1 can be found in appendix I.

4.3 Results of linear regression using relative peak power as the outcome variable

The correlation coefficient (Pearson r) between the predictor variable (jump height, S_{ft}) and outcome variable (peak relative power output (normalised to body weight)), was high (r = 0.823) and highly significant ($p < 0.001$). A scatter plot of these data is shown in Figure 4.3.

Linear regression (SPSS, Illinois) was used to predict the outcome variable, relative peak vertical mechanical power of the whole body centre of gravity (Pp_{rel} ($W.N^{-1}$)), using the predictor variable, jump height (S_{ft} (m)). The regression equation resulting from the analysis was:

$$Pp_{rel} (W.N^{-1}) = 10.187.S_{ft} (m) + 1.704 \quad \text{-------------} \quad 4.2$$

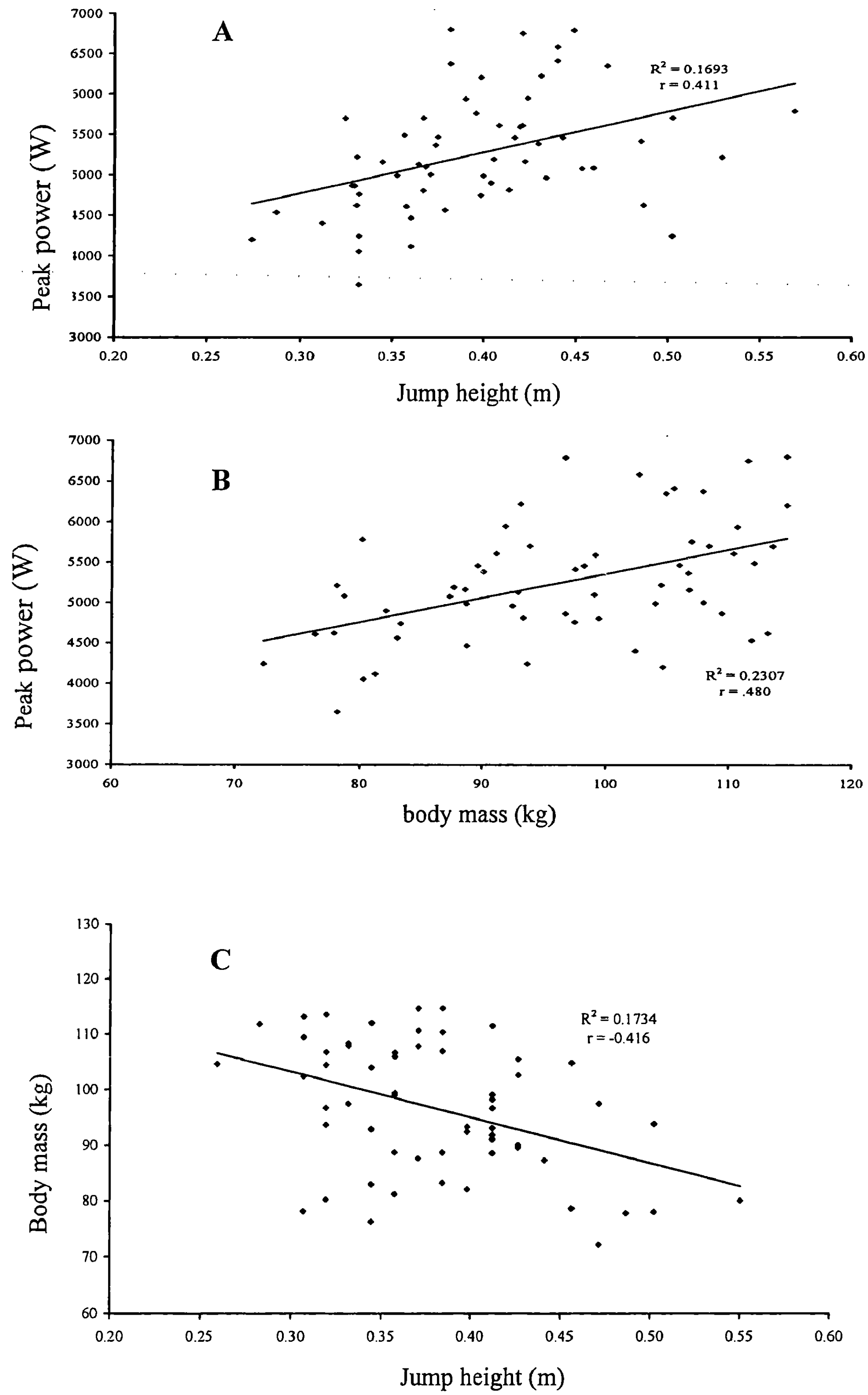


Figure 4.1 Scatter graphs of predictor variables and actual peak power. Scatter graph **A** shows the relationship between jump height and actual peak power. Scatter graph **B** shows the relationship between body mass and actual peak power. Scatter graph **C** shows the relationship between jump height and body mass.

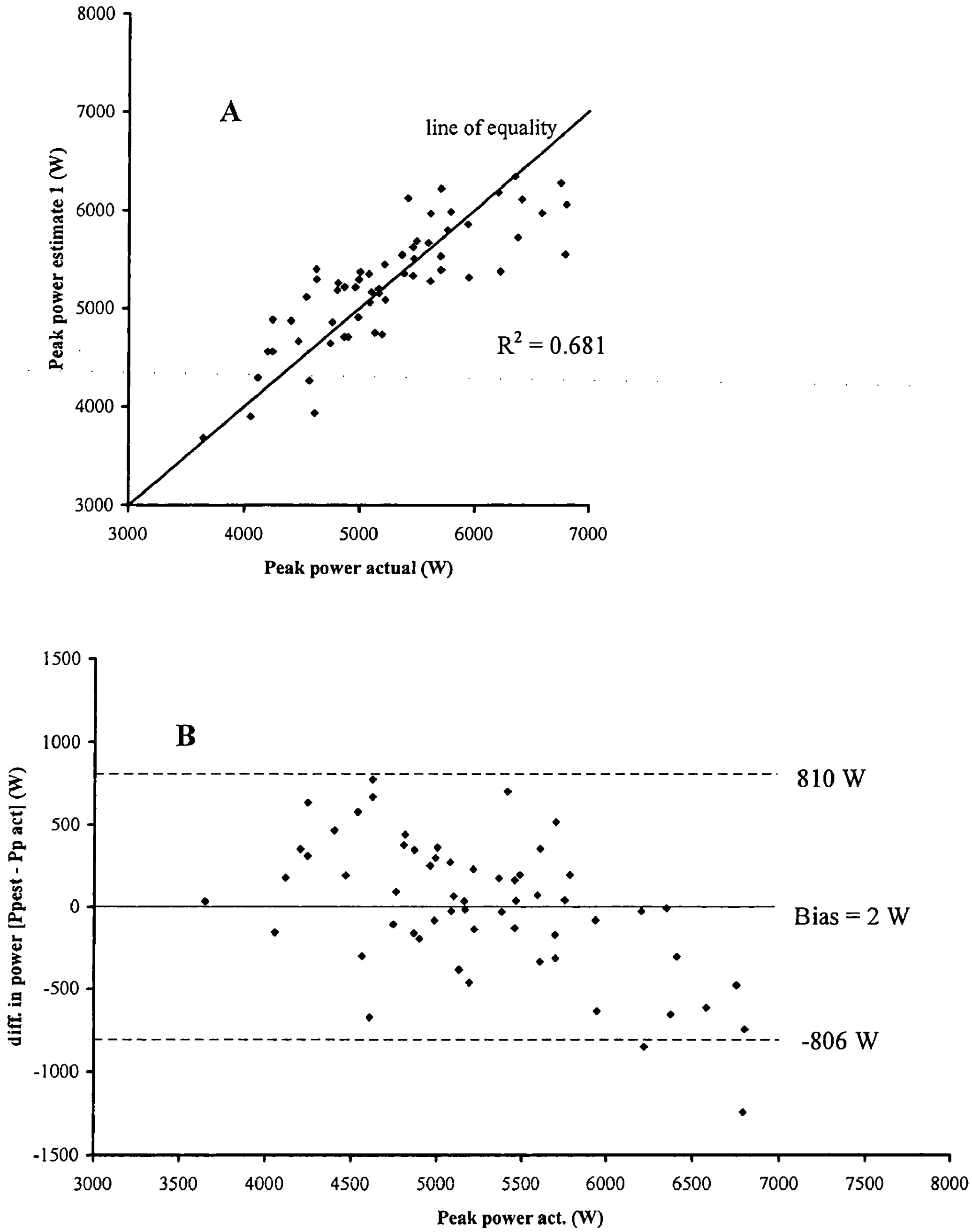


Figure 4.2 Graph **A** is a scatter graph of actual peak power and peak power estimated from equation 4.1 (estimators being jump height and body mass), graph **B** is a Bland and Altman plot comparing actual peak power with estimated peak power estimated from equation 4.1, and showing bias and limits of agreement (95% confidence interval).

Each side of equation 4.2 was then multiplied by body weight (based on equation 3.2):

$$Pp_{est2}\ (W) = [BW(N)]x[10.187.S_{ft}\ (m) + 1.704] \text{ - - - - - - - - - equation 4.3}$$

The regression equation 4.3 accounted for 72.4 % of the variation in peak power output (R^2 = 0.713) and had a standard error of the estimate of 388 W. Figure 4.4 shows a scatter graph of estimated peak power , determined using equation 4.3, and actual peak power and a Bland and Altman plot (Bland and Altman 1986) for these data. The mean peak power (actual) was 5257 W, the mean bias

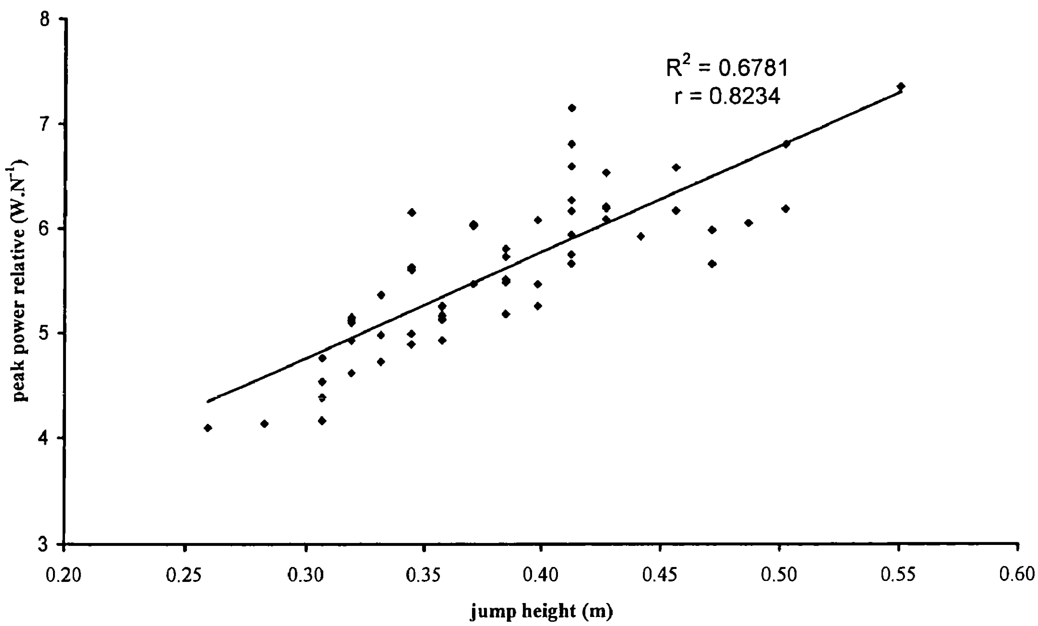


Figure 4.3 Scatter graph of predictor variable, jump height, and relative peak power (peak power normalised to body weight).

of the estimated peak power was insignificant, +7 W, and the standard deviation of the differences was 388 W giving limits of agreement of + 767 W (14.6%) and - 753 W (14.3 %). These results are summarised in Table 4.4.

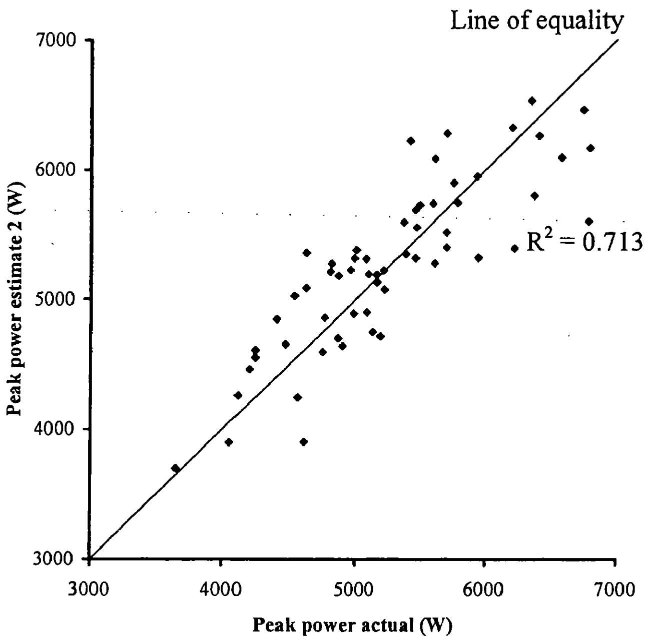
Regression equation	Pp_{est2} (W) = [BW(N)]x[10.187xS_{ft} (m) + 1.704]
Regression statistics	$R^2 = 0.713$, $p < 0.001$, S.E.E. = 388 W (7.4% of mean)
Bland and Altman statistics	Bias = 7 W, limits of agreement are +767 W (14.6 % of mean) and -753 W (14.3 % of mean), $p = 0.05$

Table 4.3 Regression equation for estimating peak vertical mechanical power of the whole body centre of gravity for a countermovement jump and regression and Bland and Altman statistics.
Pp_{est2} = peak power estimated from jump height using relative peak power, S_{ft} = jump height estimate determined from flight time, BW = body weight of subject.

A complete table of all peak powers estimated using equation 4.3 can be found in appendix J.

4.4 Comparison of the results from the absolute and relative regression equations

Table 4.5 compares the results from the absolute and relative regression equations. The relative regression equation had 5.1% less S.E.E. associated with



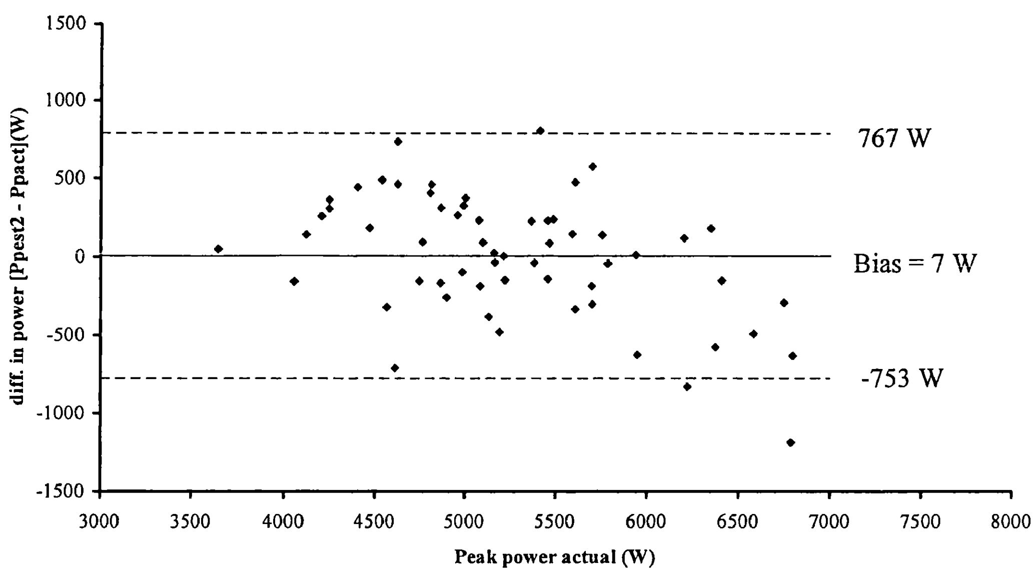


Figure 4.4 Graph **A** is a scatter graph of actual peak power and peak power estimated from equation 4.3. Graph **B** is a Bland and Altman plot comparing actual peak power with estimated peak power estimated from equation 4.3, and showing bias and limits of agreement (95% confidence interval).

the regression estimates compared to the errors associated with the absolute regression equation's estimates (expressed as a percentage of the S.E.E. of the multiple regression results).

	Absolute regression equation 4.1	Relative regression equation 4.3
r (between Pp est and Pp act)	0.824*	0.845*
R^2	0.681*	0.713*
S.E.E. (W) [% of mean Pp]	412 [7.8]	388 [7.4]
B&A bias or mean (W)	2	7
Mean + 1.96.SD (W)	810	767
Mean – 1.96.SD (W)	-806	-753

*$p<0.001$

Table 4.4 Comparison table of statistical variable for the absolute and relative regression equations

Chapter 5

Discussion

5.1 Criterion measure of instantaneous vertical mechanical power of a countermovement jump

5.2 Previous regression studies

5.3 Difference between the results of multivariate and linear regression equations

5.4 Limitations

5.5 Suitability of regression variables for field measurement

5.6 Recommendations

5.7 Further study

5.1 Criterion measure of instantaneous vertical mechanical power of a countermovement jump

Prior to any regression study being undertaken a clearly defined and valid criterion method for the measurement of criterion values is necessary. However none of the previous regression studies, investigating peak vertical mechanical power of the whole body centre of gravity of a countermovement jump (Harman et al 1991; Johnson and Bahamonde 1996; Sayers et al. 1999; Shetty 2002; Canavan and Vescovi 2003; Lara et al. 2006), provided an adequate description of the method used to obtain the criterion measure of power output in a countermovement jump using a force platform.

Previous researchers have used force platforms to determine criterion measures in vertical jumping studies (Kibele 1998; Hatze 1998) and there was a possibility of adapting their methods of force platform measurement as a criterion method for the measurement of instantaneous vertical power of a countermovement jump. However both these studies' methods had questionable validity. For example, Kibele (1998) did not appear to appreciate that the maximum vertical force experienced by a force platform is not equally divided between the four corner force transducers (section 3.2.1), and that the maximum vertical force needs to be specified in terms of corner transducers as opposed to the gross value (section 3.2.1). Hatze (1998) made no mention of vertical force range.

Consequently, it was necessary to develop a criterion method for the current study. Section 3.2.6 defines a criterion method specification which was shown, empirically, to be a valid method to measure instantaneous vertical mechanical power of the whole body centre of gravity of a countermovement jump.

5.2 Previous regression studies

The validity of the results of previous regression studies (Harman et al 1991; Johnson and Bahamonde 1996; Sayers et al. 1999; Shetty 2002; Canavan and Vescovi 2003; Lara et al. 2006) was not clear. For example, no information about the definition of the jump initiation time or method of integration used to determine instantaneous vertical velocity of the centre of gravity in a countermovement jump was provided in any of the studies (section 2.6.2). Consequently, as the validity of the results of the previous studies is not clear, the validity of the regression equations reported in the studies is also questionable, consequently, no comparisons of the previous studies' regression formulae were included in the present study.

5.3 Differences between the results of multivariate and linear regression equations

Two methods of regression analysis were used to estimate peak vertical mechanical power of the whole body centre of gravity of a countermovement jump. The first method was multivariate regression using jump height and body mass as the predictor variables and peak vertical mechanical power of the whole body centre of gravity of a countermovement jump, as measured by the criterion method, as the outcome variable. The second method, linear regression, used jump height as the predictor variable and peak vertical mechanical power of the whole body centre of gravity of a countermovement jump normalised to body weight as the outcome variable. The predicted variable, normalised peak power, was then multiplied by body weight to give an estimate in absolute units.

The linear regression equation gave more accurate results than the bivariate analysis. Linear regression accounted for 71.3 % of variation in peak power and had a S.E.E. of 388 W (7.4 % of mean peak power) as opposed to multivariate regression which only accounted for 68.1 % of variation in peak power and had a S.E.E. of 412 W (7.8 % of mean peak power). This corresponds to a reduction in the S.E.E. of 5.1 %. The Bland and Altman limits of agreement (95% CI) were reduced overall by 96 W, a 2% reduction when compared with the mean peak power. The biases for both methods were insignificant, as would be expected for a regression analysis.

A possible reason for the improved performance of the linear regression equation is that it only uses one predictor variable, as opposed to two for the multivariate regression, eliminating the need to determine the best compromise between jump height and body mass to predict a criterion measure.

5.4 Limitations

As with any regression analysis, the results are not measurements but predictions and are only accurate within certain defined limits. These limits will change if the predictor variables are not collected with the same accuracy as in this study.

Jump height is estimated from flight time, determined from time data sampled at 100 Hz. As such the jump heights will tend to have discrete, rather than continuous values. For example a subject whose flight time was 0.576 s would have the same jump height ($Sj = 0.125.g.\ 0.58^2 = 0.412$ m) as someone whose flight time was 0.584 s, both flight times being rounded off to 0.58 However a subject whose flight time was 0.585 s, only 1 ms more than 0.584, would have a jump height estimate of 0.427 m, a difference of 1.5 cm, whereas if the time data was sampled at 1000 Hz the actual difference in the estimates would have been only 2 mm. It is therefore reasonable to assume that collecting data at 100 Hz will account for some of the unexplained variation in the estimates of peak vertical mechanical power of the whole body centre of gravity of a countermovement jump.

Body mass values were determined from body weight values measured, by a calibrated force platform, during the stationary phase of the countermovement jump and were stated and used with a precision of 1 decimal place. If the same precision and accuracy is not used in the collection of body mass for use with the regression equations, the stated limits of agreement and the S.E.E. would be compromised. Also, body weight was determined at the same time that each jump was performed. If, in a field setting, body weight was measured at a different time to the jump, this could result in further errors as diurnal variation of body mass in adults can be 2 kg (Sumner and Whitacre 1931).

5.5 Suitability of regression variables for field measurement

If the regression equations developed in this study are to be used by non-specialist personnel, in a field setting, then the measurements that are necessary to use these equations would need to be simple and not open to interpretation. The only measurements that are necessary to use the regression equations are body mass and the flight time of a countermovement jump. These two measurements are suitable for field collection.

5.6 Recommendations

It is recommended that all future studies that require the measurement of instantaneous vertical mechanical power of the whole body centre of gravity in a countermovement jump, should use the criterion method described in section 3.2.6 of this study.

None of the regression equations previously published (Harman et al 1991; Johnson and Bahamonde 1996; Sayers et al. 1999; Shetty 2002, Canavan and Vescovi 2003; Lara et al. 2006) should be used to estimate the peak power outputs of any population as they are of questionable validity.

Estimation of peak vertical mechanical power of the whole body centre of gravity of a countermovement jump in young elite male rugby players in a field setting should be carried out using the linear regression equation (equation 4.3) described in this study. The predictor variables, jump height and body weight, should be measured in the following way.

Jump height estimates should be determined using a jump mat operating at a sampling frequency of 100 Hz. The subject should perform a countermovement jump, dipping to a self selected depth, with their hands placed on their hips throughout the jump. If jump height is not automatically determined by the jump mat it should be determined from the flight time using, jump height (m) = $\frac{1}{8} . g . T^2$ (where T = flight time (s) and g = acceleration due to gravity).

Body mass should be determined immediately prior to a jump. Calibrated scales, with an accuracy of 0.1 kg, should be used and these should preferably have a digital display. This would avoid the necessity of having to zero the scales and the possibility of operator error in reading a non-digital display.

5.7 Further study

This study has not investigated the accuracy with which the regression equations can track changes over time in peak vertical mechanical power of the whole body centre of gravity of a countermovement jump in young elite male rugby players. The ability to track changes is very important for coaches and as such further studies should be undertaken to establish the suitability of the equations 4.1 and 4.3 to track changes, over time, in peak power.

Whilst it is a reasonable assumption that the sampling frequency of the timing device used to measure flight time may adversely affect the prediction of peak power using the regression equations, no evidence is presented to support this. Further investigation is needed to establish if this is indeed the case and if benefits would be gained if the sampling frequency of jump mats were increased.

The population used for this study was young elite male rugby players. This population may be considered to be homogeneous with regard to age and standard of performance, but it could also be considered to be heterogeneous in relation to position played or body mass. Further studies should therefore investigate whether the S.E.E. and the limits of agreement of the regression equations could be improved if a segmentation of the population was performed.

The regression equations developed in this study were based on a population of young elite male rugby players. No information was sought as to how valid these equations are with regard to other populations. Therefore further investigations should be undertaken to assess the validity of these equations for use with other populations, including senior club rugby players and senior regional rugby players. If the equations were found to be unsuitable for a particular population, then the methodology and procedures developed in this study could be applied to the population in order to develop a population specific regression equation.

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Appendices

Appendix A. Ethical approval

Appendix B. Subject information form

Appendix C. Subject consent form

Appendix D. Maximum component force values

Appendix E. Peak power at different sampling frequencies

Appendix F. Effect of varying initiation time of jump

Appendix G. Peak power determined using different numerical integration methods

Appendix H. Initial data collected using the criterion method

Appendix I. Results of multivariate regression

Appendix J. Results of linear regression

Appendix A: Ethical Approval

Swansea University
DEPARTMENT OF SPORTS SCIENCE
DEPARTMENTAL ETHICS ADVISORY COMMITTEE

APPLICATION FOR ETHICAL COMMITTEE APPROVAL OF A RESEARCH PROJECT

In accordance with Departmental Safety Policy, all research undertaken in the department must be approved by the Departmental Ethics Advisory Committee **prior to** data collection. **Applications for approval should be typewritten on this form using the template available in the Public Folders.** The researcher(s) should complete the form in consultation with the project supervisor. Where appropriate, the application must include the following appendices:
(A) subject information sheet;
(B) subject consent form;
(C) subject health questionnaire.

After completing sections 1-12 of the form, 1 copy of the form should be handed-in to the Department Administrator who will then submit copies of the application for consideration by the Departmental Ethics Advisory Committee. The applicant(s) will be informed of the decision of the Committee in due course.

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1. DRAFT TITLE OF PROJECT
Development of a field test to estimate mechanical leg power in elite rugby union players

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2. NAMES AND STATUS OF RESEARCH TEAM
Nicholas Owen – Postgraduate student
Prof. James Watkins - Supervisor

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3. RATIONALE
Rugby union is a popular contact sport worldwide with attendance figures of up to 70,000 per match for internationals (Maud and Schultz 1984). The physical fitness requirements for rugby are that players should exhibit high levels of aerobic endurance, strength and power (Nicholas 1997). The general fitness requirements for rugby are well known, however more specific muscle function tests are less well developed, for example tests of muscular power. Power in the arms, legs and trunk are considered important attributes for performance in rugby (Nicholas 1997), therefore power testing should form part of any regular assessment of muscular performance (Cronin and Hansen 2005). A useful test of leg power is the countermovement vertical jump (Newton and Dugan 2002) and has been used for many years in a variety of forms (Fox and Mathews 1972, Morton 1978, McLean 1992, Harman et al. 1991, Johnson and Bahamonde 1996, Sayers et al. 1999, Newton and Dugan 2002, Canavan and Vescovi 2004). The criterion method of measuring instantaneous leg power in a countermovement jump requires the use of a force platform to determine force-time and velocity-time histories of a subject performing a countermovement jump, with the power being defined as the product of velocity and force (Winter 2005). Whilst this method is a valid and well justified criterion method (Hatze 1998) it also requires the use of expensive equipment that is not usually available for field testing.

There are a number of methods of estimating peak mechanical power output based on performance in a countermovement jump (Fox and Mathews 1974, Harman et al 1991, Johnson and Bahamonde 1996, Sayers et al 1999, Shetty 2002, Canavan and Vescovi 2003, Lara et al 2006). These estimates require the collection of countermovement jump variables that are easier to measure than those required in the criterion method, and thus are more suitable for field collection. These field measurements are stature, body mass and jump height. Whilst these estimates are well established there is currently no information regarding their validity with regard to elite rugby union players. The purpose of the proposed study is to investigate the validity of existing methods of estimating peak vertical mechanical leg power produced by elite rugby union players performing a countermovement jump.

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McLean, D.A. (1992). Analysis of physical demands of international rugby union. Journal of Sports Science, 10; 285-296.

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5. AIMS and OBJECTIVES

The aim of the study is to investigate the validity of existing estimates of peak vertical mechanical leg power produced in a countermovement jump for elite rugby union players.

The objectives of the study are:

1. Determine peak vertical mechanical power output produced in a countermovement jump for a group of elite rugby union players using the criterion method.
2. Determine the validity of existing methods of estimating peak vertical mechanical power output produced in a countermovement jump for the same group of elite rugby union players.
3. If necessary develop a population specific method of estimating peak vertical mechanical power output produced in a countermovement jump for a group of elite rugby union players.

6. METHODOLOGY

6.1 Study Design

Approximately 70 subjects from the WRU's academy squads will participate in this study. All subjects will be familiar with the testing procedure as it forms part of their current testing battery. For each subject a criterion measure of peak vertical mechanical power output produced in a maximal countermovement jump will be made. Comparisons with existing methods of estimating peak vertical mechanical power output produced in a maximal countermovement jump will then be made.

6.2 Experimental Procedures

After having their stature measured, subjects will complete a pre-defined warm-up. Each subject will then perform a maximal countermovement jump off a force platform.

6.3 Data Analysis Techniques

A criterion measure of peak leg power will be determined from the recorded force-time history using the relationship power = force x velocity. To simulate the use of a jump mat (which would be used in a field setting to measure jump height) flight times will be determined from the force-time history. Flight time will then be used to estimate jump height using the equation, jump height = $\frac{1}{8}.g.T^2$. Body mass will be derived from body weight, determined using the force platform. Body mass, jump height and stature will be used as the input variables to existing methods of estimating peak vertical mechanical power output produced in a maximal countermovement jump and will be compared to the criterion method.

6.4 Storage and Disposal of Data and Samples

Data will only be available to members of the research team and subjects will remain anonymous.

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7. LOCATION OF THE PREMISES WHERE THE RESEARCH WILL BE CONDUCTED.

Welsh Rugby Union, The Barn, Vale of Glamorgan CF72 8JY

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8. SUBJECT RISKS AND DISCOMFORTS

There is little risk of injury or discomfort as subjects are only required to perform a single, maximal countermovement jump.

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9. INFORMATION SHEET AND INFORMED CONSENT

Have you included a Subject Information Sheet for the participants of the study ? YES

Have you included a Subject Consent Form for the participants of the study? YES

---

10. COMPUTERS

Are computers to be used to store data? YES

If so, is the data registered under the Data Protection Act? YES

---

11. STUDENT DECLARATION

Please read the following declarations carefully and provide details below of any ways in which your project deviates from them. Having done this, each student listed in section 2 is required to sign where indicated.

1. I have ensured that there will be no active deception of participants.
2. I have ensured that no data will be personally identifiable.
3. I have ensured that no participant should suffer any undue physical or psychological discomfort
4. I certify that there will be no administration of potentially harmful drugs, medicines or foodstuffs.
5. I will obtain written permission from an appropriate authority before recruiting members of any outside institution as participants.
6. I certify that the participants will not experience any potentially unpleasant stimulation or

deprivation.
7. I certify that any ethical considerations raised by this proposal have been discussed in detail with my supervisor.
8. I certify that the above statements are true with the following exception(s):
9. All collected data will be destroyed immediately after completion of the project.

Student signature: (include a signature for each student in research team)

Date: 5/1/04

12. SUPERVISOR'S DECLARATION

In the supervisor's opinion, this project (delete those that do not apply):

- Does not raise any significant issues.
- ~~Raises some ethical issues, but I consider that appropriate steps and precautions have been taken and I have approved the proposal.~~
- ~~Raises ethical issues that need to be considered by the Departmental Ethics Committee.~~
- ~~Raises ethical issues such that it should not be allowed to proceed in its current form.~~

Supervisor's signature: James Watkins Date: 10/1/04

13. ETHICS COMMITTEE DECISION (COMMITTEE USE ONLY)

ETHICAL APPROVAL: GRANTED REJECTED (delete as appropriate)

The ethical issues raised by this project have been considered by members of the Departmental Ethical Approval Committee who made the following comments:

....

....

....

....

....

....

Please ensure that you take account of these comments and prepare a revised submission that should be shown to your supervisor/ resubmitted to the Department Ethical Approval Committee (delete as appropriate).

Signed: M.J. Lemon Date: 10/1/04

(Chair, Departmental Ethics Advisory Committee)

DEPARTMENT OF SPORTS SCIENCE

SUBJECT INFORMATION SHEET

Date :

Contact Details:

Nick Owen
Department of Sports Science,
7th Floor Vivian Tower,
Swansea University,
Singleton Park,
Swansea SA2 8PP.
tel 01792 513099

1. Study title

Development of a field test to estimate leg power in elite rugby union players

2. Invitation paragraph

You are invited to take part in a study that aims to develop a method of estimating leg power in elite rugby union players. Taking part will involve you performing a single countermovement jump.

3. What is the purpose of this study?

This study aims to develop a method of estimating leg power in elite rugby union players.

4. Why have I been chosen?

You have been invited to take part in this study because you are a member of one of the four WRU academy squads and as such are an elite rugby union player.

5. What will happen to me if I take part?

You will be asked to complete you normal pre-training warm-up. You will the have your height measured, after which you will be asked to perform a single, maximal countermovement jump off a piece of equipment known as a force platform. The jump will be no different to the jump you normally perform in training.

6. What are the possible disadvantages of taking part?

There are no disadvantages in taking part

7. What are the possible benefits of taking part?

The aim of the study is to provide rugby coaches with an easy and non-expensive method of estimating leg power. Estimates of leg power can then be used to personalise the training program of individuals without the need for costly equipment.

8. Will my taking part in the study be kept confidential?

Your privacy will be respected at all times and you will remain anonymous throughout the study. The results of the study will be used in my thesis and may be published in academic research papers.

Appendix C: Subject consent form

DEPARTMENT OF SPORTS SCIENCE
SUBJECT CONSENT FORM

Contact Details:

Nick Owen
Department of Sports Science,
7th Floor Vivian Tower,
Swansea University,
Singleton Park,
Swansea SA2 8PP.
tel 01792 513099

Project Title:
Development of a field test to estimate leg power in elite rugby union players

Please initial box

1. I confirm that I have read and understood the information sheet dated ....../....../...... (version number ....) for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐

3. I understand that sections of any of data obtained may be looked at by responsible individuals from the University of Wales Swansea or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records. ☐

4. I agree to take part in the above study.

______________________	____________	____________________
Name of Subject	Date	Signature
______________________	____________	____________________
Name of Person taking consent	Date	Signature
______________________	____________	____________________
Researcher	Date	Signature

Appendix C: Subject consent form

DEPARTMENT OF SPORTS SCIENCE
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4. I agree to take part in the above study.

____________________	__________	________________
Name of Subject	Date	Signature
____________________	__________	________________
Name of Person taking consent	Date	Signature
____________________	__________	________________
Researcher	Date	Signature

Appendix D: Maximum component force values

	Subject	$F_{z\,max}$ (N)	$F_{zc\,max}$ (N)	$F_{zc\,max}$ as % of $F_{z\,max}$	BW (N)
Fowards	1	2860	1100	38	1061
	2	2600	1100	42	1166
	3	2750	1100	40	1045
	4	2600	1210	47	1152
	5	2260	900	40	1015
	6	2540	1050	41	1161
	7	2950	1000	34	1155
	8	2270	820	36	1016
Backs	9	2500	1080	43	922
	10	2150	800	37	890
	11	2390	810	34	943
	12	2230	920	41	958
	13	2060	770	37	799
	14	2370	980	41	818
	15	2340	1080	46	979

Whole group	min =	2060	770	37	799
	max =	2950	1210	41	1166
	mean =	2458	981	40	1005
	SD =	260	137	53	121
Forwards	min F =	2260	820	36	1015
	max F =	2950	1210	41	1166
	mean F =	2604	1035	40	1096
	SD F =	251	125	50	68
Backs	min B =	2060	770	37	799
	max B =	2500	1080	43	979
	mean B =	2291	920	40	901
	SD B =	152	132	86	69

Table D.1 Vertical ground reactioin force data for countermovement jumps performed by 15 international rugby players.

$F_{z\,max}$ = maximum resultant vertical ground reaction force

$F_{zc\,max}$ = maximum of the corner component vertical ground reaction forces

Appendix E: Peak powers at different sampling frequenies

Subject	BW(N)	Pp_{1000}(W)	Pp_{500}(W)	Pp_{100}(W)
1	1167	5239	5241	5323
2	1015	5560	5571	5618
3	979	5111	5118	5211
4	818	4736	4751	4833
5	1061	5965	5972	6110
6	1161	5063	5071	5151
7	1045	4555	4550	4605
8	1152	5934	5949	6013
9	1155	5647	5637	5706
10	799	4747	4765	4901

mean	1035	5256	5263	5347
SD	137	504	504	505

Table E.1 Peak vertical mechanical power produced in a countermovement jump by 15 international rugby players calculated from force-time histories sampled at 1000 Hz, 500 Hz and 100 Hz.
BW = body weight
Pp_{1000} = peak power calculated from force-time histories sampled at 1000 Hz
Pp_{500} = peak power calculated from force-time histories sampled at 500 Hz
Pp_{100} = peak power calculated from force-time histories sampled at 100 Hz

Appendix F: Effect of varying initiation time of jump

Subject	time relative to t_s (ms)							
	-40	-30	-20	-10	0	+10	+20	+30
	Instantaneous power (W)[integration start at t_s - 100 ms]							
1	0	0	0	0	-1	-6	-16	-28
2	1	1	1	2	3	4	6	7
3	1	-1	0	-1	-3	-5	-10	-15
4	-4	-6	-6	-5	-3	0	5	9
5	1	0	1	2	3	6	9	11
6	-1	-2	-2	-3	-5	-6	-8	-10
7	2	-1	0	1	3	6	11	16
8	4	3	3	3	1	-1	-4	-5
9	-2	-3	-3	-2	0	1	3	4
10	2	-1	-1	-1	-3	-5	-8	-10

mean =	0.4	-1.0	-0.7	-0.4	-0.5	-0.6	-1.2	-2.1
SD =	2.3	2.4	2.5	2.5	3.0	4.8	9.2	13.8
3.SD =	6.8	7.2	7.5	7.5	8.9	14.4	27.5	41.4

Table F.1 Instantaneous vertical mechanical power at times relative to t_s for 10 international rugby players performing a countermovemmentjump. Integration was started at t_s - 100 ms. t s was defined as the the instant, after the signal to jump had been given, that the ground reaction force exceeded body weight ± 5 standard deviations.

Appendix G: Peak power determined using different numerical integration methods

Subject	Simpson's rule Pp_{1000}(W)	Trapezoidal rule Pp_{1000}(W)
1	5239	5228
2	5560	5547
3	5111	5100
4	4736	4723
5	5965	5948
6	5063	5050
7	4555	4549
8	5934	5921
9	5647	5634
10	4747	4730

mean =	5256	5243
SD =	504	503

Table G.1 Peak vertical mechanical power produced in a countermovement jump for 10 international rugby players. Peak power was determined using two different methods of numerical integration.
Pp_{1000} = peak power determined from a force-time history sampled at 1000 Hz

Appendix H: Results of criterion method of peak vertical mechanical power output

subject	BW (N)	Mass (kg)	Pp (W)	S_{ft} (m)
1	1093.6	111.5	6748	0.412
2	763.4	77.8	4622	0.487
3	883.5	90.1	5382	0.427
4	1124.9	114.7	6202	0.384
5	805.3	82.1	4898	0.398
6	868.8	88.6	5164	0.412
7	787.2	80.3	4054	0.319
8	900.9	91.9	5945	0.412
9	1006.5	102.6	6580	0.427
10	1039.1	106.0	5465	0.357
11	906.8	92.5	4959	0.398
12	971.9	99.1	5591	0.412
13	785.8	80.1	5784	0.550
14	1047.2	106.8	5159	0.319
15	974.8	99.4	4804	0.357
16	1024.6	104.5	5220	0.319
17	913.0	93.1	6221	0.412
18	859.8	87.7	5191	0.371
19	1057.7	107.9	6373	0.371
20	918.9	93.7	4243	0.319
21	708.4	72.2	4243	0.471
22	1062.8	108.4	5700	0.331
23	748.4	76.3	4608	0.344
24	948.8	96.8	4864	0.319
25	817.0	83.3	4744	0.384
26	1048.9	107.0	5755	0.384
27	956.3	97.5	5414	0.471
28	796.7	81.2	4116	0.357
29	878.7	89.6	5457	0.427
30	1046.4	106.7	5365	0.357

subject	BW (N)	Mass (kg)	Pp (W)	S_{ft} (m)
31	1124.6	114.7	6796	0.371
32	1109.9	113.2	4621	0.306
33	1028.2	104.8	6347	0.456
34	765.4	78.0	5213	0.502
35	1026.2	104.6	4201	0.259
36	1082.3	110.4	5607	0.384
37	1073.2	109.4	4866	0.306
38	971.2	99.0	5098	0.357
39	1004.1	102.4	4401	0.306
40	1058.6	107.9	5002	0.331
41	1096.9	111.9	4535	0.282
42	963.2	98.2	5456	0.412
43	1085.2	110.7	5935	0.371
44	1034.3	105.5	6408	0.427
45	870	88.7	4985	0.384
46	766.3	78.1	3647	0.306
47	955.9	97.5	4760	0.331
48	920.6	93.9	5700	0.502
49	911.1	92.9	5130	0.344
50	915.4	93.3	4812	0.398
51	814.2	83.0	4562	0.344
52	948.1	96.7	6787	0.412
53	1020	104.0	4990	0.344
54	856.6	87.3	5077	0.441
55	1098.9	112.1	5487	0.344
56	1113.6	113.6	5698	0.319
57	870.2	88.7	4467	0.357
58	893.6	91.1	5608	0.412
59	771.6	78.7	5084	0.456

Mean	947.4	96.6	5257	0.381
SD	114.8	11.7	728	0.059

Table H.1 Initial data collected for regression analysis, body weight (BW), body mass (Mass), peak instantaneous vertical mechanical power, (Pp), of the whole body centre of gravity during the propulsion phase of a countermovement jump and jump height, (S_{ft}), estimated from flight time derived from 100 Hz force-time history.

Appendix I: Results of multivariate regression

subject	Pp act (W)	Pp est(W)
1	6748	6271
2	4622	5292
3	5382	5352
4	6202	6175
5	4898	4704
6	5164	5149
7	4054	3897
8	5945	5309
9	6580	5966
10	5465	5503
11	4959	5211
12	5591	5663
13	5784	5979
14	5159	5195
15	4804	5182
16	5220	5082
17	6221	5369
18	5191	4729
19	6373	5717
20	4243	4555
21	4243	4879
22	5700	5387
23	4608	3934
24	4864	4704
25	4744	4638
26	5755	5796
27	5414	6117
28	4116	4293
29	5457	5328
30	5365	5540

subject	Pp act (W)	Pp est(W)
31	6796	6051
32	4621	5396
33	6347	6340
34	5213	5442
35	4201	4554
36	5607	5962
37	4866	5213
38	5098	5164
39	4401	4868
40	5002	5366
41	4535	5115
42	5456	5620
43	5935	5854
44	6408	6104
45	4985	4902
46	3647	3681
47	4760	4853
48	5700	6217
49	5130	4746
50	4812	5254
51	4562	4262
52	6787	5545
53	4990	5290
54	5077	5349
55	5487	5683
56	5698	5527
57	4467	4660
58	5608	5273
59	5084	5058

mean =	5257	5259
SD =	728	601

Table I.1 Actual and estimated peak vertical mechanical power output produce in a countermovement jump for 59 elite rugby players.
Pp act = actual peak power measured using the criterion method
Pp est = peak power estimated using multivariate regression

Appendix J: Results of linear regression

subject	Pp act (W)	Pp est(W)
1	6748	6457
2	4622	5084
3	5382	5346
4	6202	6322
5	4898	4639
6	5164	5130
7	4054	3898
8	5945	5320
9	6580	6090
10	5465	5554
11	4959	5224
12	5591	5739
13	5784	5744
14	5159	5186
15	4804	5211
16	5220	5074
17	6221	5391
18	5191	4713
19	6373	5798
20	4243	4550
21	4243	4607
22	5700	5400
23	4608	3900
24	4864	4698
25	4744	4591
26	5755	5895
27	5414	6220
28	4116	4259
29	5457	5317
30	5365	5593

subject	Pp act (W)	Pp est(W)
31	6796	6164
32	4621	5356
33	6347	6530
34	5213	5219
35	4201	4460
36	5607	6082
37	4866	5179
38	5098	5191
39	4401	4846
40	5002	5378
41	4535	5025
42	5456	5687
43	5935	5948
44	6408	6258
45	4985	4889
46	3647	3698
47	4760	4856
48	5700	6277
49	5130	4748
50	4812	5274
51	4562	4243
52	6787	5598
53	4990	5316
54	5077	5310
55	5487	5727
56	5698	5514
57	4467	4651
58	5608	5276
59	5084	4900

mean =	5257	5264
SD =	728	648

Table J.1 Actual and estimated peak vertical mechanical power output produce in a countermovement jump for 59 elite rugby players.
Pp act = actual peak power measured using the criterion method
Pp est = peak power estimated using linear regression