Developing a Criterion Method for Assessing Countermovement Jump Variables in Children Aged 7 to 11 Years

Christopher Mark Jones

Submitted to Swansea University in fulfilment of the requirements for the Degree of
Doctor of Philosophy

Swansea University

2018

“For every action there is an equal and opposite reaction”

Sir Isaac Newton *1643-1727*

Abstract

Measuring countermovement jump (CMJ) variables such as instantaneous peak mechanical power output (PPO) in children has been shown to be associated with a wide variety of factors such as measuring bone health and identifying children at risk of motor disorders. Yet, how PPO and other variables are attained lack validity as no criterion method or methods of estimating CMJ variables have been developed for children (aged 7 to 11 years). Therefore, the aim of this thesis was to develop a criterion method for assessing PPO in children. This thesis also sought to develop prediction equations for estimating PPO. *Experimental Chapter 1* found absolute differences in unprocessed CMJ variables between elite adults and children highlighting that a new criterion method was needed for children. *Experimental Chapter 2* established that CMJ variables that do not account for body size need to represent children by 2 groups, whereas, if body size is accounted then children can be represented as one homogenous group. The findings of this chapter demonstrated that that more than one criterion method was needed to be developed for children. *Experimental Chapter 3* developed two criterion methods for assessing PPO from a CMJ for children, reporting a less stringent specification for the children criterion methods when compared to the elite adult criterion method specifications. Having achieved the first part of the thesis aim *Experimental Chapter 4* developed a number of regression equations to estimate PPO in children to enable practitioners who do not have access to force platforms to have a means of estimating PPO by easily measured variables in the field such as body mass and flight height. In conclusion, this thesis has made significant steps in providing a standardised method of measuring or estimating PPO and other CMJ variables in children aged 7 to 11 years for future researchers.

Summary of Publications

Jones, C.M., McNarry, M.A., Owen, N.J. (Under Review). The Effect of Age and Sex on Countermovement Jump Kinetics in Children Aged 7 to 11 Years and Elite Adults.

Jones, C.M., McNarry, M.A., Owen, N.J. (Under Review). The Effect of Body Size on Countermovement Jump Kinetics in Children Aged 7 to 11 Years.

Jones, C.M., Owen, N.J. (Under Review). Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump in Children Aged 7 to 11 Years.

Jones, C.M., McNarry, M.A., Owen, N.J. (Under Review). Development of a Field-Based Test to Estimate Peak Mechanical Power Output in Children Aged 7 to 11 Years.

Declarations and Statements

1. I, Christopher Mark Jones, hereby declares that the work presented in this thesis has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.
2. I, Christopher Mark Jones, hereby declares that the thesis is the result of my own investigations, except where otherwise stated and that other sources are acknowledged by footnotes giving explicit references and that a bibliography is appended.
3. I, Christopher Mark Jones, hereby gives consent for the thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed: [redacted] (candidate)

Date: *March 2017*

Contents Page

Acknowledgements

Though words cannot convey my feelings, I would like to take this opportunity to thank those who supported myself in the completion of this thesis. The end of this thesis completes an 8 year journey at Swansea University, from undergraduate to postgraduate. It has been an absolute privilege to study and develop personally and professionally at this institution.

I would especially like to thank my supervisor Nickolas Owen for his continual advice and guidance throughout this process. I could not have completed this thesis without your help, intellect, and time. Every meeting you would provide myself with a new insight and I thank you for my professional development and for continually pursuing into the unknown.

To Dr Melitta McNarry who took the helm of second supervisor halfway through this thesis, I thank you for your swift feedback and valued guidance especially for Experimental Chapter 2. I would like to thank Professor Steve Mellalieu who was my second supervisor during the first year of my PhD. You provided me with a lot of guidance and professional support throughout my time at Swansea. I would also like to thank my examiners, Professor Mike Lewis and Dr Peter Mundy for their fair, critical and engaging approach to my viva voce examination.

To my family and friends, I thank you for your love and support throughout this long and winding process. To my mum and dad, Helen and Mark Jones who gave me the opportunity to do this PhD though there love and financial support. You are two fantastic parents and I wish to offer my love and hopefully return your financial support in kind one day. To Paul and Gran thank you for food and lodging free of charge, during part of this thesis. Your generosity and kindness is remarkable and I thank you. To my late Grandad you were an absolute legend and are missed sorely.

Lastly, I would like to dedicate this entire thesis to Lorraine. You have been with me every step of the way from the highs to the lows. You stepped up every day to support us whilst I was pursuing this. Words cannot express the love and appreciation I have for you. I owe you everything and I promise to make it up to you for the rest of our lives for the sacrifices you have made as a result of my choices. You have my heart.

List of Figures

List of Tables

List of Equations

List of Abbreviations

ABRFD	-	Allometric basic rate of force development
AC	-	Alternating current
ACSM	-	American College of Sports Medicine
ADC	-	Analogue to digital converter
AFmax	-	Allometric peak force
AHA	-	American heart association
AIFR	-	Allometric in jump vertical force range
AIMF	-	Allometric in jump vertical minimum force range
ANOVA	-	Analysis of variance
A-STEM	-	Applied Sport Technology Exercise and Medicine Research Centre
b	-	Coefficient value
b	-	Constant
b_0		Regression constant
b_1	-	Regression coefficient value
BM	-	Body mass
BRFD	-	Basic rate of force development
BW	-	Body weight
CMJ	-	Countermovement Jump
CoG	-	Whole body centre of gravity
CRB	-	Criminal Records Bureau
CV	-	Coefficient of variation
d.p.	-	Decimal place

DBS	-	Disclosure and Barring Service
DC	-	Direct current
dF/dt	-	1st derivative of force
EACM	-	Elite adult criterion method
E-C	-	Eccentric to concentric
ES	-	Effect size
F	-	F value
FA	-	Force of attraction
F/T	-	Force-time
FH	-	Flight Height
Fmax	-	Peak Force
FP	-	Force platform
FPM	-	Force platform method
f_0	-	Frequency harmonic
F/T	-	Force-time history
FT	-	Flight-time
F_t	-	Corresponding instantaneous force at time t
Fx	-	Medial-lateral force
Fy	-	Anterior-posterior force
Fz	-	Vertical force
g	-	Acceleration due to gravity 9.81 $m.s^{-2}$
GPS	-	Global Positioning system
h_1	-	Displacement of CoG during propulsive phase
h_d	-	Depth of countermovement

h_r	-	Reach height
Hz	-	Hertz
ICC	-	Intraclass correlation coefficient
IFR	-	In-jump vertical force range
IFRt	-	In-jump vertical force range time
IMF	-	In-jump vertical minimum force
J	-	Impulse
JH	-	Jump height
LPT	-	Linear position transducer
MPO	-	Mean mechanical power output
MVC	-	Maximal voluntary contraction
η_p^2	-	Partial eta squared/effect size
n	-	Number
n.d.	-	No date
NBRFD	-	Normalised basic rate of force development
NFmax	-	Normalised peak force
NIFR	-	Normalised in jump vertical force range
NIMF	-	Normalised in jump vertical minimum force
NM	-	Neuromuscular performance
NPD	-	Normalised percentage difference
NR	-	Not reported
p	-	Probability value

P	-	Momentum
P	-	Mechanical Power
PPO	-	Instantaneous peak mechanical power output
PRV	-	Peak power output reference value
P_t	-	Corresponding instantaneous mechanical power at time t
r	-	Pearson R correlation
R^2	-	Coefficient of determination
RFD	-	Rate of force development
SD	-	Standard deviation
SE	-	Strain energy
SI	-	Système International d'Unités
SJ	-	Squat Jump
SME	-	Simple main effects
SPSS	-	Statistical package for the social sciences
SSC	-	Stretch shortening cycle
SSE	-	Standard error of estimates
T	-	Total flight-time
t	-	T value
t_i	-	Start time
t_s	-	Initiation time
T_{td}	-	Landing time
T_{to}	-	Take-off time
u	-	Initial velocity
UK	-	United Kingdom

UKSCA	-	United Kingdom Strength and Conditioning Association
v	-	Final velocity
v_{ti}	-	change in velocity interval
v_t	-	Corresponding instantaneous velocity at time t
VGRF	-	Vertical component of the ground reaction force
VJ	-	Vertical jump
WD	-	Work done
X	-	Medial-lateral axis
Y	-	Anterior-posterior axis
y_a	-	Allometrically scaled variables
y_e	-	Estimated regression value
Z	-	Vertical axis

Chapter 1 General Introduction

1.1 The Assessment of Neuromuscular Performance in Children

Human performance can be quantified by neuromuscular performance of the body and the technical execution of the required task or skill. The neuromuscular system can be defined as the interaction between the nervous system and muscular systems in the control of joint movements (Watkins, 2014). Neuromuscular performance describes the force-generating capacity of the muscle (Place, Yamada, Bruton, & Westerblad, 2010; Weir, 2006). One of the most common methods of measuring lower body neuromuscular performance in applied research is a form of vertical jumping called the countermovement jump (CMJ) performed on a force platform (FP), which quantifies lower body neuromuscular performance in terms of force, work, impulse, velocity, displacement, power and time (Gissis et al., 2006; Owen, Watkins, Kilduff, Bevan, & Bennett, 2014; Quatman, 2005; Walsh, Böhm, Butterfield, & Santhosam, 2007). Neuromuscular performance CMJ variables such as, jump height (JH), rate of force development (RFD), peak force (Fmax) and most notably lower body instantaneous peak mechanical power output (PPO) has been closely associated with a wide variety of important factors in child populations such as measuring the effects overweight and obesity (Bovet, Auguste, & Burdette, 2007), used as an indicator of bone strength and health (Schoenau & Fricke, 2008; Weeks, Young, & Beck, 2008), used to monitor maturation status (Beunen, 1988; Lloyd, Oliver, Faigenbaum, Myer, & De Ste Croix, 2014; Malina, Bouchard, & Bar-Or, 2005) and used as measure coordination (Clark, Phillips, & R, 1989; Korff, Horne, Cullen, & Blazevich, 2009), which could be used to identify children with motor disorders such as children with developmental coordination disorders (DCD). Though the interpretation of many of these studies utilising CMJs as a measure of lower body neuromuscular performance in children (PPO, RFD and JH) are confounded by methodological limitations, such as the lack of key specification necessary to determine their validity (Busche, Rawer, Rakhimi, Lang, & Martin, 2013; Focke et al., 2013; Gabel, Macdonald, Nettlefold, Race, & McKay, 2016; Lang, Busche, Rakhimi, Rawer, & Martin, 2013; Sumnik et al., 2013). Consequently, this has produced a number of studies with unclear results (Duncan, Hankey, Lyons, James, & Nevill, 2013; Focke et al., 2013; Gabel et al., 2016; Knudson, 2009; Raffalt, Alkjær, & Simonsen, 2016a; Sumnik et al., 2013; M. J. D.

Taylor, Cohen, Voss, & Sandercock, 2010). When assessing human movement or collecting any type of data it is critical that the data collected is valid and reliable. Although, the significance may not be apparent this can severely reduce the positive impact that can be made from the results. For example, if the CMJ variable PPO was used as an objective measure of coordination in order to help identify children with motor disorders as it requires the child to produce the right force at the right velocity to execute the skill of jumping effectively. If the methods in which deriving CMJ neuromuscular performance variable PPO in children was not valid or reliable. This could result in erroneous conclusions that would be unclear and incomparable, whilst potentially giving a child the wrong intervention or diagnosis. This is considerably important especially in children with motor disorders such as DCD which have long waiting lists to seek professional help due to over referrals of children who do not have DCD, and 75% of cases of children with DCD not identified until the end stages of primary school (Holsti, Grunau, & Whitfield, 2002; Kirby, Sugden, & Purcell, 2014). The ability to mass screen and identify children with DCD early is of vast importance as, as an early intervention programme is more likely to improve coordination and motor skills and as a direct result increase self-esteem, socialisation and enjoyment (Holsti et al., 2002; Kirby et al., 2014).While the absence of an effective remediation programme has shown problems associated with DCD to still persist later in life, with nearly 60-75% of children diagnosed with DCD will have difficulties as adults either psychiatric, psychological problems or turn to crime during adolescence (Cantell, Smyth, & Ahonen, 1994; Losse et al., 1991). Therefore, it is essential that primary children (aged 7 to 11 years) have a valid means of measuring countermovement jump variables or a means of estimating these variables as none currently exist or have been developed for child populations. For example, if researchers collect the CMJ variable PPO without first employing a criterion method, the reported results will be unclear as errors will occur when deriving the output variable or the equipment used may not meet the required specification to collect meaningful data in children (Busche et al., 2013; Focke et al., 2013; Gabel et al., 2016; Sumnik et al., 2013). Furthermore, if adult developed regression equations are used to estimate PPO in children as FP are expensive and limited to organisations with large budgets (Duncan, Hankey, & Nevill, 2013), the lower body mass in children coupled with the higher negative intercept values from adult models will result in a misrepresentation of the actual power values generated in the child and in some cases attain values that are biologically and biomechanically implausible (Duncan, Hankey, & Nevill, 2013).

There is only one reported criterion method for deriving CMJ F/T history data, however this was developed for elite adults (EACM). Consequently, it would be reasonable to investigate the need or not for similar standard (or criterion) methods for children aged 7 to 11 years as the EACM and specification could be over specified or even invalid for such a population. In order to determine whether the current EACM is suitable for children aged 7 to 11 years, the absolute differences between the two populations must to be compared. However, limited information is currently available comparing child and adult CMJ performance measured via a FP. Although significant differences may be anticipated, it remains to be reported which parameters differ and the magnitude of difference. Indeed only six previous studies have investigated CMJ F/T history variables via a FP (Busche et al., 2013; Focke et al., 2013; Gabel et al., 2016; Sumnik et al., 2013), with only three study directly comparing children and young adults (Gabel et al., 2016; Raffalt, Alkjær, & Simonsen, 2016b; Raffalt et al., 2016a). However, the findings of these studies remain largely unclear, due to a number of CMJ variables being reported that require a developed criterion method prior to their calculation. For example, Raffalt, Alkjaer & Simonsen. (2016b) demonstrated that jump JH was significantly higher and less variable in 20 male adults when compared to 11 male boys, whereas allometrically scaled knee joint power and Fmax were greater in children. The results of this study are in accord with Focke et al. (2013) who demonstrated that JH increased with age whereas, relative Fmax and RFD decreased or remained constant. Furthermore, significant sex differences have been reported in children, with boys having significantly larger values for absolute JH and girls having significantly larger values for normalised Fmax and RFD. In contrast, Sumnik et al. (2013) and Busche et al. (2013) utilised jumping mechanography to provide reference data for absolute Fmax and PPO from a CMJ with arm swing highlighting that significant age effects occurred for PPO, JH and Fmax with no significant sex differences occurring until 12 years of age (Busche et al., 2013; Gabel et al., 2016; Sumnik et al., 2013). The reason for the discrepancies between these studies is presently unclear as further interpretations are limited by certain methodological limitations such as the techniques used to attain F/T history CMJ variables. Therefore, variables that do not need a criterion method prior to their calculation must be identified so that they can used across age, sex and population. Furthermore, the discrepancies found within the findings of CMJ variables in child populations may be a result of the interchangeable use of absolute values and values that account for body size such as normalising and allometric scaling. For example, a study by Focke et al. (2013) investigated the effects of age, sex and activity level on CMJ performance in children and adolescents. The results showed that absolute jump height (JH) increased significantly with age, whereas when JH was normalised to body height, the influence of age was ameliorated. If JH was reported only as an absolute or normalised value the findings in result would be limited and potentially unclear for comparison. It has not yet known the full impact of accounting for body size in children, in terms of how the results are interpreted, and are grouped. For example, would more than one criterion method needed to be develop for children aged 7 to 11 years or would one method be satisfactory to collect valid CMJ PPO data.

1.2 Objectives of the Thesis

Therefore, the aim of this thesis is to develop a criterion method for assessing countermovement jump variables in children aged 7 to 11 years. This thesis also sought to develop prediction equations for estimating PPO in the field once the criterion method for assessing countermove jump variables was developed. To achieve this aim, a series of research objectives and questions were proposed:

I. To investigate the effect of age and sex on CMJ variables in children aged to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children.. Specifically, the objective will aim to answer the following questions:
   a. What countermovement jump variables can be measured across age, sex and population?
   b. What differences are there between children aged 7 to 11 years and elite adult's absolute countermovement jump variables?

II. To investigate the importance of accounting for body size in the interpretation of countermovement jump kinetics in children aged 7 to 11 years. Specifically the objective will aim to answer the following questions:
   a. Is more than one criterion method needed for measuring countermovement jump variables in children aged 7 to 11 years?

b. What impact does body size have on interpreting countermovement jump kinetics in children aged 7 to 11 years?

III. To develop a criterion method to determine peak mechanical power output in a CMJ in children aged 7 to 11 years. Specifically, the objective will aim to answer the following questions:

a. What vertical force range and resolution is needed to measure peak mechanical power output in children aged 7 to 11 years?

b. What sampling frequency is needed to measure peak mechanical power output aged 7 to 11 years?

c. What initiation of start time is needed to measure peak mechanical power output in children aged 7 to 11 years?

IV. To use regression analysis to estimate of lower body peak mechanical power output in children aged 7 to 11 years. Specifically, the objective will aim to answer the following question:

a. Can lower body peak mechanical power output be estimated as function of easily measured variables in the field in children aged 7 to 11 years?

1.3 Organisation of the Thesis

The organisation of this thesis consists of 10 chapters. Chapter 2 consists of a critical review of the literature, discussing the previous research and underpinning methodological approach used within this thesis. Chapter 3 describes the general methods employed to obtain the kinetic data used in the subsequent chapters of this thesis. Participants, experimental procedures, data processing and analyses are all described in detail within this chapter. Chapter 4 (*Experimental Chapter 1),* investigates the effect of age and sex on unprocessed neuromuscular jumping kinetic variables. A prominent focus of this chapter is the need for valid and reliable specifications in order to attain derived neuromuscular variables such as peak power, and jump height. This chapter compares the effects of unprocessed neuromuscular kinetic variables from a CMJ in elite adults and children aged 7 to 11 years. The aim of this chapter was to characterise the differences in absolute CMJ kinetics between children aged 7 to 11 years and elite adults to determine whether the current elite CMJ adult criterion method should be re-evaluated for children. Chapter 5 (*Experimental Chapter 2),* investigates the effects of age and sex on unprocessed neuromuscular jumping kinetic variables within children aged 7 to 11 year group. This chapter will establish the differences of absolute, normalised and allometric CMJ kinetics within children in order to determine whether more than one criterion method should be developed for children aged 7 to 11 years. Chapter 6 (*Experimental Chapter 3),* determines the specifications needed for measuring lower body instantaneous peak mechanical power in a CMJ for children aged 7 to 11 years. The aim of this chapter was to establish the specifications needed for the measurement of lower body instantaneous peak mechanical power output and other CMJ variables for child schools years 3 and 4 and school years 5 and 6 using the force platform criterion method. Chapter 7 (*Experimental Chapter 4),* describes the development of estimates peak mechanical power output in children aged 7 to 11 years. The aim of this chapter was to investigate the validity of field test which estimate lower body peak mechanical power output in children aged 7 to 11 years in order to provide a cheaper alternative to the criterion force platform method. Chapter 8 discusses the major findings of this thesis, along with an appraisal of methods used and the insight that has been gained. The research questions established in Chapter 1 are sequentially addressed to meet the thesis aim, and implications of the results of each research question are discussed. Limitations of the research are outlined, along with recommendations for the direction of future research. This will enable the continuation of a greater understanding of assessing neuromuscular variables in child populations. Chapters 9 contains the references used throughout this thesis and Chapter 10 is the thesis appendix containing the information sheets, consent forms and additional methods.

Chapter 2 Review of Literature

2.1 Introduction

The following literature review is presented in seven t sections. Section 2.2 summaries vertical jumping as a measure of lower limb neuromuscular performance outlining the key positions, kinetics and kinematics involved with a countermovement jump (CMJ). Section 2.3 reviews the various methods of assessing performance in a CMJ, highlighting that the criterion method of measuring CMJ performance is via a force platform (FP). Section 2.4 discusses the use of FP method to assess lower limb neuromuscular performance, highlighting a number of key factors that must be considered if measuring a number of variables such as mechanical power. Section 2.5 details the criterion method for determining instantaneous peak mechanical power output in elite adults. Section 2.6 reviews the current methods of assessing mechanical power in children, aiming to demonstrating that the development of a criterion method for children is essential for further research. Appendix V provides a small extension to the literature review describing the definitions and biomechanical calculations of neuromuscular variables used throughout this thesis.

2.2 Vertical Jumping as a Measure of Lower Limb Neuromuscular Performance

Vertical jumping has been used extensively as a measure of lower limb neuromuscular performance, typically expressed in terms of force, work, velocity, displacement, power and time. A wide variety of vertical jumps exist such as running, standing, weighted, and unilateral equivalents. The most common form of vertical jumping used within performance testing is standing. There are two main types of standing vertical jumps, the squat jump (SJ) and the countermovement jump (CMJ). The CMJ is commonly preferred to the SJ, as the CMJ has been shown to be more ecologically valid with regards to sprinting and running due to the CMJ utilizing the stretch shortening cycle (SSC), which also elicits greater neuromuscular performance values (Cronin & Hansen, 2005; Cunningham et al., 2013; Linthorne, 2001; Watkins, 2014; West et al., 2011). The greater performance observed in a CMJ when compared to the SJ is largely due to the difference in storage and utilisation of elastic strain energy in the connective tissue of the leg extensor musculotendinous units, and the amount of force produced by the muscle components of the leg extensor (Watkins, 2014). Therefore, when discussing vertical jump performance throughout this thesis it refers to a CMJ.

A CMJ can be performed with arm swing, as a measure of gross total body neuromuscular performance, or with arms akimbo (no arm swing and hand remain on hips) as a measure of lower limb neuromuscular performance. The use of arm swing has been found to create additional force during standing vertical jumps (Payne et al, 1968), increase height at take-off (Lees, Vanrenterghem, & Clercq, 2004) and faster take-off velocities by 6-72% (Feltner, Fraschetti, & Crisp, 1999; Lees, Vanrenterghem, & Clercq, 2004) which has resulted in greater jump height (JH) by 5-28 % (Harman, Rosenstein, Frykman, & Rosenstein, 1991; Lees, Vanrenterghem, & Clercq, 2004; Payne, Slater, & Telford, 1968; Shetty & Etnyre, 1989). However, the use of arm swing when performing a CMJ should be implemented with caution, as unwanted variations in CMJ performance variables can occur due to coordination and technique issues. The corresponding neuromuscular performance value obtained, therefore, may not reflect the athlete's true neuromuscular performance. The elimination of arm swing enables the isolation of the lower body and may reduce the bias of skill seen in tests that utilise arm swing. Therefore, when discussing a CMJ throughout this thesis it is in regards to arms akimbo in order to isolate the lower body and remove unwanted variation in jump performance.

2.2.1 The Countermovement Jump

All variants of the CMJ have certain elements in common. A participant starts the movement in the upright position. The jump is then initiated by a simultaneous flexion of the hips, knees and ankle joints, lowering the whole body's centre of gravity (CoG). This initial movement by which the body develops speed of movement in the opposite direction to that of the final movement is known as the absorption or eccentric phase (Watkins, 2014). Before the final movement can be initiated, the movement of the body in the opposite direction must be arrested. Consequently, the muscles must contract to arrest the movement of the body and in doing so they are forcibly stretched and as such act eccentrically (Watkins, 2014). The eccentric phase is then followed immediately by the propulsion or concentric phase, which involves a simultaneous extension of the hips, knees, and ankle joints, where sufficient upward speed of the CoG is generated to lift the body off the ground (Bartlett, 1997). This pattern of movement whereby an eccentric action is followed without pause by a concentric action is referred to as the stretch shortening cycle (Watkins, 2014).

2.2.2 Kinematic and Kinetics of the Vertical Motion of the Whole Body Centre of Gravity in a Countermovement Jump

Figure 2.2.1 shows the sequence of the key positions for a generic CMJ and the corresponding force-time, acceleration-time, velocity-time and displacement time histories. The indication of the start time of the jumper is indicated by point [a]. The individual's is initially standing upright and is stationary (Linthorne, 2001). The change in an individual's velocity and vertical displacement are brought about by forces acting on the jumper due to gravity and coordinated muscle activity. Therefore, when the individual is stationary the resultant force acting on the individual must be zero, as the vertical component of the ground reaction force (VGRF) acting on the participant is equal to the individual's weight (Owen, 2008). The change from point [b] to point [a] occurs when the participant relaxes their leg and hip muscles and allowing their knees and hips to flex under the effects of gravity (Linthorne, 2001). Any reduction in VGRF would result in a downward resultant force acting on the individual and consequently a downward acceleration of the CoG. The resultant negative impulse (Figure 2.2.2) would result in downward velocity of the CoG (Owen, 2008). The maximum downward acceleration of the CoG is marked by point [b]. If the VGRF was greater than the bodyweight of the individual there would be a resultant upward force acting on the individual and either downward or upward acceleration of the CoG, resulting in a decrease in downward velocity or upward velocity of the CoG. The period between [b] to [c] is the time when the CoG is still moving downward but the jumper has started to increase the activation of the leg muscles. The downward acceleration of the CoG starts to decrease even though downward velocity of the CoG is still increasing as the resultant force of the participant is still negative. Point [c] indicates the maximal downward velocity of the CoG and the VGRF is equal to bodyweight, therefore, the resultant force of the jumper and thus the acceleration of the CoG must equal zero. This is further supported by previous literature showing that the maximum upward vertical velocity during jumping is not at the instant of take-off, but at a short time before take-off (Dapena & Chung, 1988; Lees, Graham-Smith, & Flower, 1994).

The period between [*a*] to [*c*] is called the 'first unweighting phase' as the VGRF is less than bodyweight. Figure 2.2.2 shows the impulse of the resultant force relating to the VGRF acting on the individual performing a CMJ. The initial impulse (the first unweighting phase) applied to the CoG produces a downward velocity. Before the participant can start to move upward, the downward velocity of the CoG must be reduced to zero. By creating an equal but opposite positive impulse, this is known as the first weighting phase (point [*c*] to [*d*]). Activation of the leg muscles results in a positive acceleration even though the CoG is still moving downwards. Point [*d*] indicates the initial negative impulse is equal to the positive impulse therefore, the velocity of the CoG is now zero, and this point is the maximum downward displacement of the CoG. A common error when examining the force–time curve is to identify point [*b*] as the lowest point of the countermovement (Linthorne, 2001). The change in displacement of the CoG from point [*a*] to [*d*] is the depth of the countermovement (h_d). The period between points [*d*] to [*e*] is known as the push-off phase, where the jumper moves upwards by extending the knees and hips. This creates a positive velocity of the CoG which is generated by the remaining positive impulse (second weighting phase). For many jumpers, the maximum VGRF value occurs early in the push-off phase, shortly after the lowest point of the countermovement. The maximum upward velocity of the CoG is achieved just before take-off marked by point [*e*]. Point [*e*] also identifies the point at which the VGRF has dropped to become equal to bodyweight and therefore, the resultant force of the jumper and acceleration of the CoG is equal to zero. The period between [*e*] to [*f*] identifies the reach height (h_r) of the CoG, which is the displacement of the CoG at take-off relative to the starting position. This period also marks when the VGRF drops bodyweight creating a small negative impulse known as the 'second unweighting phase' (Figure 2.2.2). Even though the CoG is moving upward a small decrease in the CoG velocity occurs due to the effects of gravity. Point [*f*] highlights the instant of take-off where the ground reaction force first becomes zero and the CoG is now higher than initiation of the jump due to extension of the ankle joints. The change in displacement of the CoG during the propulsive phase (h_1) occurs from point [*d*] to point [*f*]. When the jumper is airborne the only force acting on the jumper is the jumper's bodyweight and the trajectory of the CoG is the same as a projectile in the absence of air resistance. Consequently, the trajectory of the CoG can be determined by applying the equations of uniformly accelerate motion. The region [f] to [g] marks the ascent of the flight phase, whereby the CoG is moving upward but slowing down due to the effect of gravity. Point [g] marks the peak displacement of the CoG, which is also momentarily at rest. The period between point [a] and point [g] is referred to as jump height (JH) which is defined as the height gained by the CoG above starting height (Owen et al., 2014). The period between points [g] to [h] marks the descent of the flight phase, where the CoG is moving downward as a result of the increase in negative velocity from the effects of gravity. Point [h] is the instant of landing, where the feet first contact the ground. The VGRF shows a sharp impact peak and eventually becomes equal to bodyweight when the jumper is again standing motionless on the force platform which is not shown. The time between the instant of take-off (point [f]) and that of landing (point [h]) is termed the flight-time and the height gained by the CoG between these points is referred to as flight height (FH).

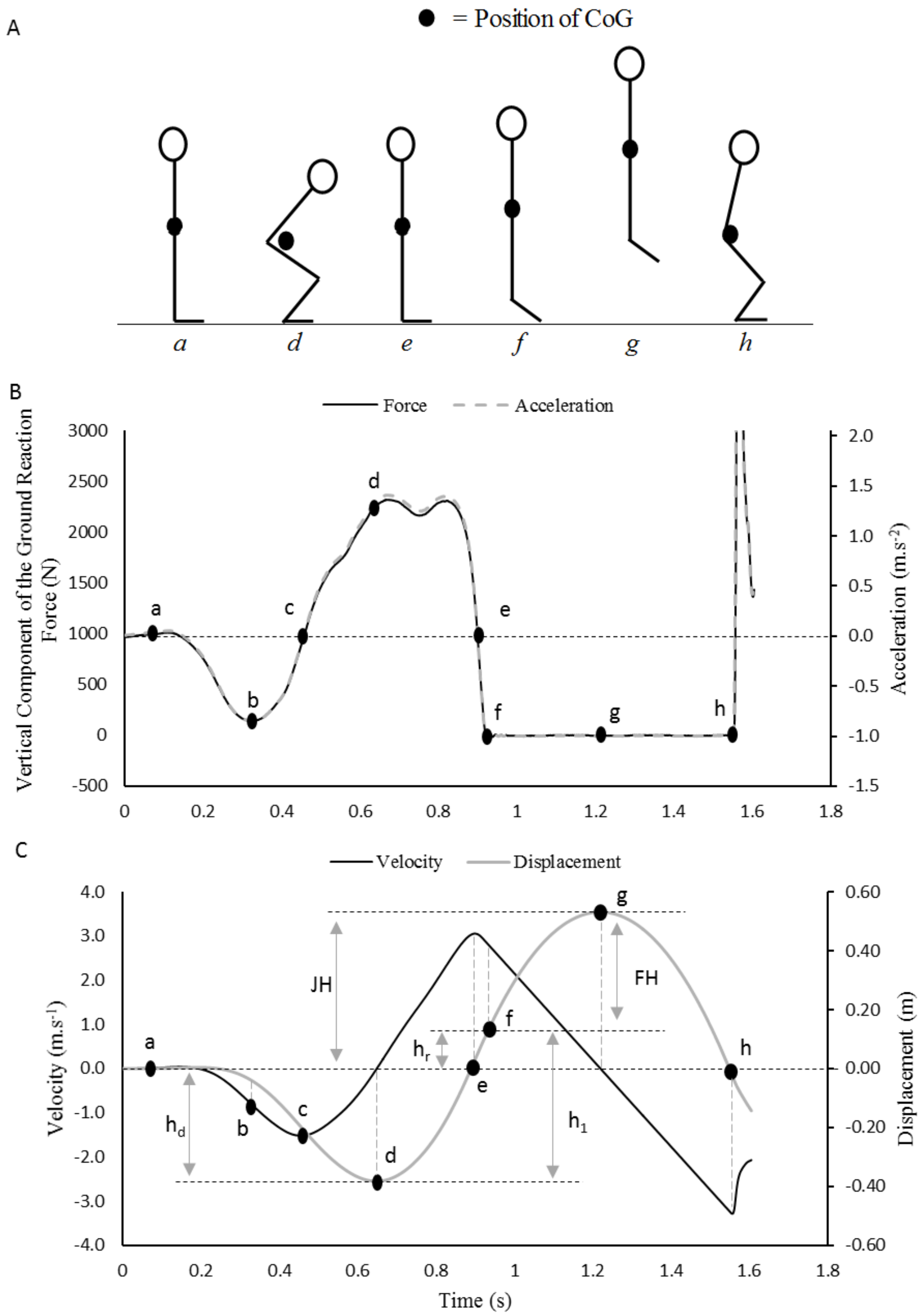

Figure 2.2. 1. Countermovement Jump A = sequence of actions, B = corresponding force and acceleration-time histories, and C = corresponding velocity and displacement-time histories of the whole body centre of gravity in a countermovement jump. Adapted from Linthorne. (2001) and Owen. (2008)

a = start of the jump

b = maximum downward acceleration of the CoG

c = maximum downward velocity of the CoG

d = maximal downward displacement of the CoG

e = maximum upward velocity of the CoG

f = instant of take-off

g = peak vertical displacement of the CoG

h = instant of landing

h_d = *depth of countermovement*

JH = jump height, height gained by the CoG above starting height

h_r = *reach height, the height at take-off relative to the starting position*

h_1 = *displacement of the CoG during propulsive phase* = $h_d + h_r$

FH = flight height, height gained by the CoG after take-off = FH - h_r

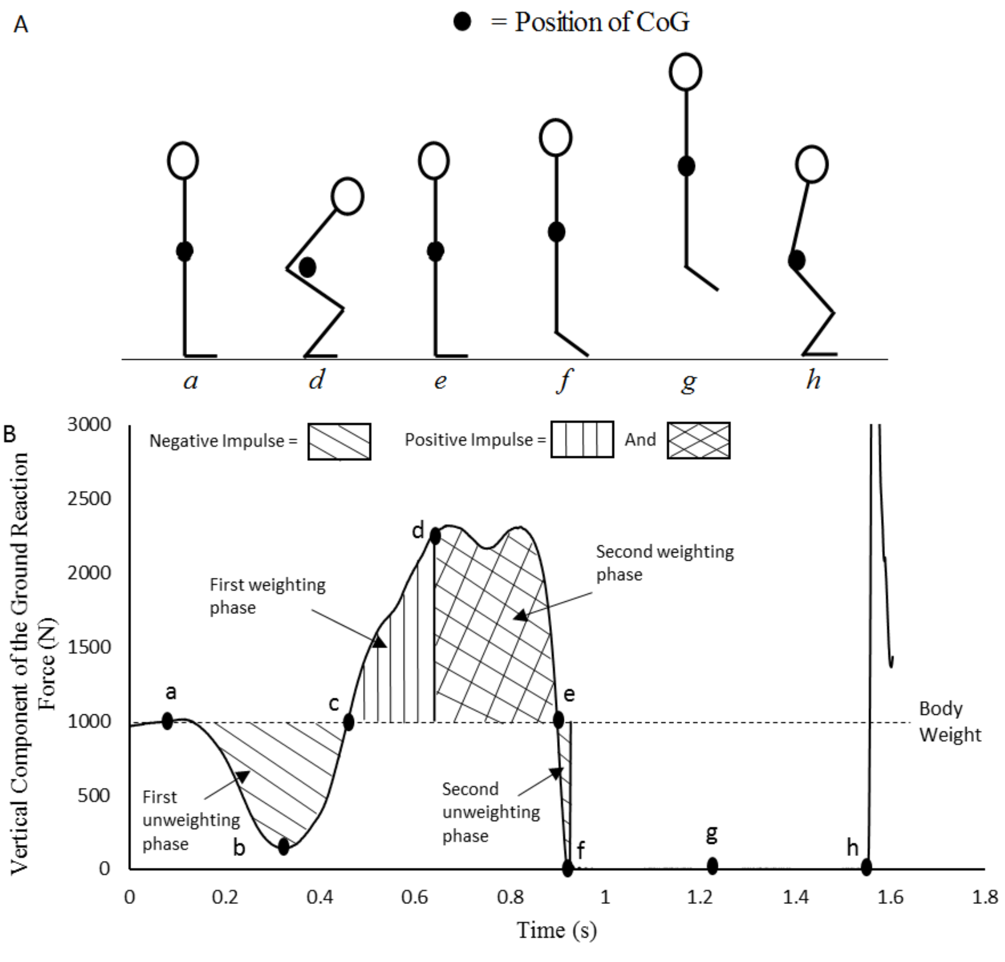

Figure 2.2. 2. Countermovement jump where A = position sequence, B = vertical component of the ground reaction force-time history showing the relationship between the impulse of the vertical resultant force and the corresponding position of the jumper.

Positions a, b, c, d, e, f, g and h correspond to Figure 2.2.1

2.3 Methods of Assessing Performance in a Countermovement Jump

Countermovement jumps (CMJ) have been used as the basis of testing a variety of neuromuscular variables that are considered key to successful sporting performance (Bobbert & van Ingen Schenau, 1988; Cronin & Hansen, 2005; Hay, 1992; Kawamori et al., 2005; Kilduff et al., 2007; Owen et al., 2014; Wright, Pustina, Mikat, & Kernozek, 2011). The measurement of neuromuscular variables has been used as strength diagnostics, quantification of training status and talent identification in youth (Owen et al., 2014). Traditionally, the most common form of measuring a CMJ has been the Sargent jump, also known as the jump and reach test (Sargent, 1924). Gray et al. (1962) later proposed a jump and reach test that estimated average leg power, based on the change in gravitational potential energy during the propulsion and flight phases. Subsequently, Davies & Rennie. (1968) proposed a method of measuring instantaneous vertical mechanical power output of a CMJ by means of a force platform (FP). This has now become the criterion method for the determination of neuromuscular performance variables such as jump height (JH), peak force (Fmax), rate of force development (RFD), and mechanical power from a CMJ (Canavan & Vescovi, 2004; Harman, Rosenstein, Frykman, & Rosenstein, 1991; Hatze, 1998; Kibele, 1998; Owen et al., 2014; Sayers, Harackiewicz, Harman, Frykman, & Rosenstein, 1999). However, due to the cost of a FP, it is not used universally within the literature to measure CMJ neuromuscular performance. Four methods of assessing CMJ neuromuscular performance have been identified: (1) The jump and reach method, (2) flight-time method, (3) linear position transducer method and (4) force platform method. The following section will discuss each method.

2.3.1 Jump and Reach Method

The first assessment of a CMJ was the Sargent Jump or jump and reach (Sargent, 1924), the participants finger tips of the preferred hand dusted with powered chalk, performs a static reach to mark a wall or vertical board as high as possible whilst standing on tip toes. The participant then performs a CMJ in order to make a second mark on the wall between the two marks i.e. the height jump and standing height (Figure 2.4.1). The vertical distance between the two marks is recorded as an indirect measure of the participant’s leg power (Blattner & Noble, 1979; Clutch, Wilton, McGown, & Bryce, 1983; Genuario & Dolgener, 1980). This is represented in Figure 2.3.1.

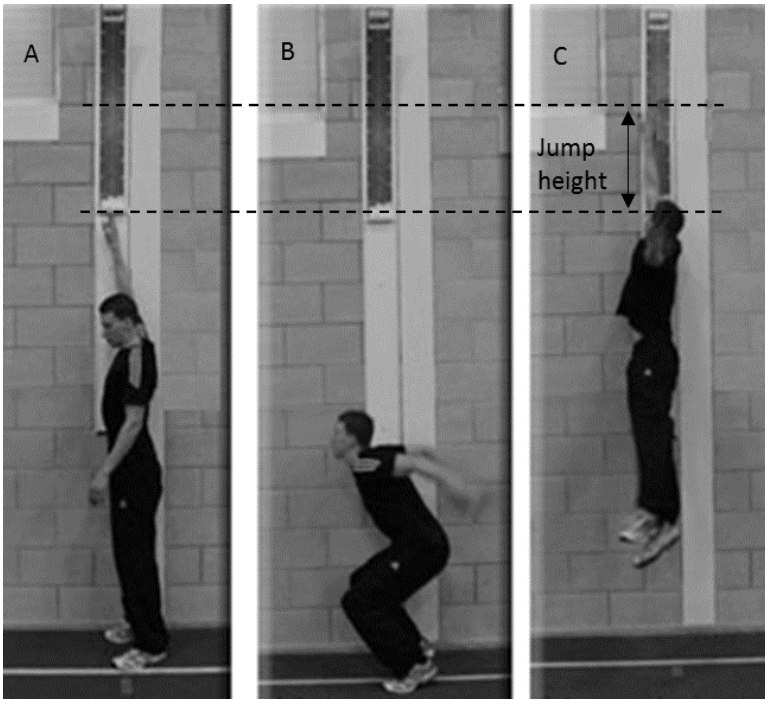

Figure 2.3. 1. The jump and reach test.

Where A = standing reach height, B = countermovement with arm swing, C = jump reach height

A more recent variant of this test utilises plastic markers mounted on a vertical stand that are caused to rotate when tapped by the participant to indicate the static reach height and JH (Vertec^{Tm} jump trainer, VertiMax Inc., Tampa, United States). Previous research by Johnson & Nelson. (1979) has reported a reliability of 0.93 which is in agreement which Glencross. (1966) who found a test-retest reliability of r > 0.92 and coefficient of variation 2.0 - 5.0% in adults (Cormack, Newton, McGulgan, & Doyle, 2008; Moir, Garcia, & Dwyer, 2009). However, as previously stated the contribution of arm swing on jump performance enhances momentum and is thought to increase JH by 28% in adults (Lees, Vanrenterghem, & De Clercq, 2004). In addition, with contribution of stretch shortening cycle this nearly doubles the variability seen in performance if children when compared to adults (Gerodimos et al., 2008) due to timing and technique. Therefore, the JH may not reflect the participant’s actual lower limb neuromuscular performance.

2.3.2 Flight-Time Method

When a participant performs a CMJ a number of devices such as an instrumented jump mat, accelerometers and smart phones on interfaces can record the flight-time. The most commonly reported device within the literature which utilizes the flight-time method for assessing lower limb CMJ performance is an instrumented mat. The instrumented jump mat records the flight-time (FT) of the CMJ which is the time between take-off (point [f] and landing (point [h] Figure 2.3.2) (Carlock et al., 2004). Micro switches in the instrumented jump mat create an electrical circuit when a participant takes-off, which starts a timer, and stops the timer when the participant lands again (Whitmer et al., 2014). The flight-time of the CMJ is then used to determine the flight height (FH) of a participant (Bosco, Luhtanen, & Komi, 1983; de Salles, Vasconcellos, de Salles, Fonseca, & Dantas, 2012), which is defined as the height gained by the whole body centre of gravity CoG after take-off (Bosco et al., 1983; Owen et al., 2014). This is algebraically expressed as:

$$FH = \frac{1}{8} \cdot g \cdot T^2$$

Equation 1

Where FH = flight height (m), T = total flight-time (s) and g = acceleration due to gravity of the earth (9.81 m.s^{-2}) (Kibele, 1998).

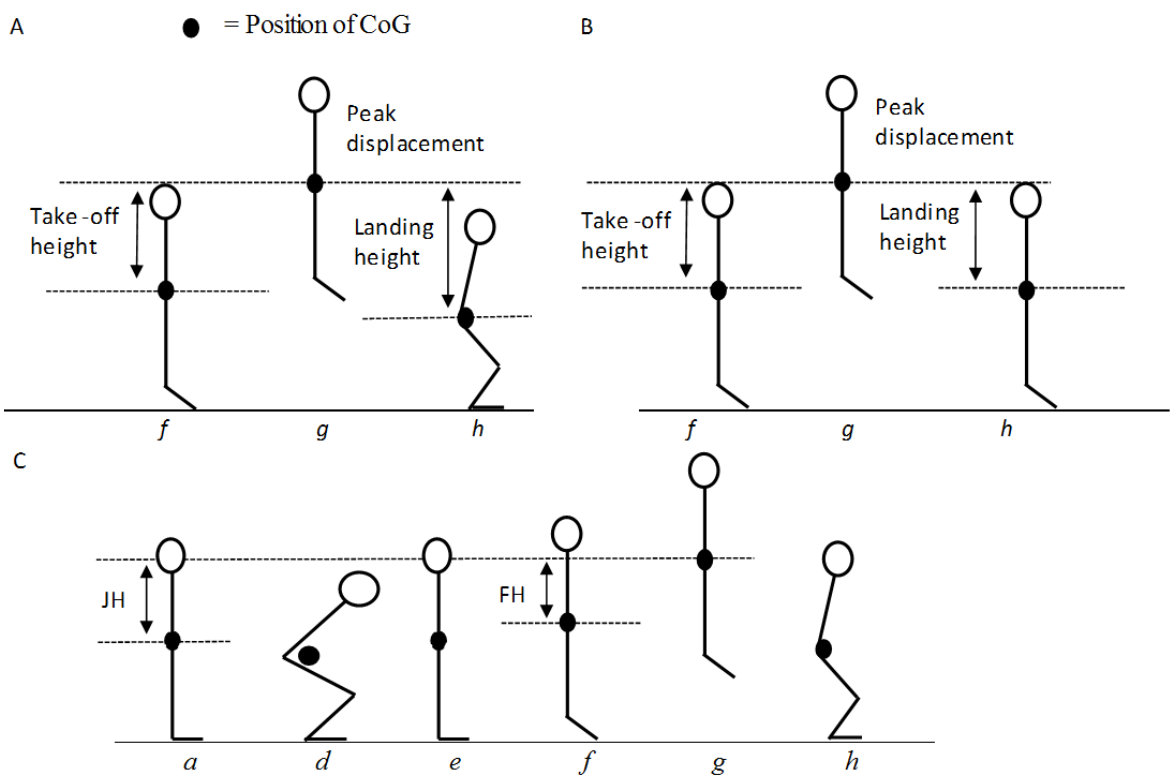

Figure 2.3. 2. Take-off and landing of a countermovement jump with A = typical landing, B = landing height same as take-off height and C = differences between jump height and flight height.

Whereby JH = jump height and FH = flight height. Positions a, b, c, d, e, f, g and h correspond to Figure 2.2.1

In order for this method to be valid, the assumption that the participant's take-off height and landing height are the same must be met (Figure 2.3.2B). The total flight–time of a participant performing a CMJ is separated into two phases: time up (point [*f*] to point [*g*] Figure 2.3.2) and time down (point [*g*] to point [*h*] Figure 2.3.2). When the take-off and landing height are the same, the flight-time up is the same as the flight-time down. However, if the landing height is not the same as take-off height, the flight-time up will not be the same as flight-time down which will result in errors in the attained flight height value. For example, Figure 2.3.2 illustrates a participant performing two CMJs that achieve the same flight heights, but with different landing heights. Figure 2.3.2B highlights the landing height of CMJ A as the same as take-off height. Figure 2.3.2A demonstrates a smaller landing height when compared to take-off height for CMJ B. A lower landing height is typically as a result of an increase in angular ankle and knee displacement in order to absorb and reduce the rate of loading from the landing impact force. This will consequently cause the flight-time down to be longer than the flight-time up. This will result in an increased value for total flight-time for condition A irrespective of the fact that the same FH was achieved in the two scenarios. If the flight-time method was used to measure FH for both conditions, CMJ A would overestimate the height gained by CoG after take-off (Linthorne, 2001).

The limitation associated with the flight-time method may account for the problems reported within the literature with regards to instrumented jump mats measuring flight height. The instrumented jump mats have demonstrated inconsistent flight-times and consequently higher calculated FH values when compared to the criterion FP method (Whitmer et al., 2014). Other factors such as the sampling frequencies of the instrumented jump mat may account for some of this variation found when compared to the FP method. Instrumented jump mats typically sample at either 100 Hz or 500 Hz depending on the cost and sophistication of the system (Balsalobre-Fernández, Glaister, & Lockey, 2015; Owen, 2008). A CMJ occurs in less than 0.7 seconds and due to the high force and velocity when measuring elite adults and sportsmen sampling below 1000 Hz will result in less accurate results (Owen et al., 2014). Therefore, if the sampling rate of the timing device within a jump mat is below 1000 Hz, it may miss the actual take-off and landing time points. This might suggest why previous research has shown the Just Jump timing mat (Probotics, Inc. Huntsville Alabama) to demonstrate coefficient of variation of 4.2% (Moir, Button, Glaister, & Stone, 2004) and 2.4% (Nuzzo, McBride, Cormie, & Mccaulley, 2008).

A final note is that the flight-time method does not determine the JH of the participant but the FH as seen in (Figure 2.3.2C). Though subtly different, many researchers within the literature are unaware of the difference between the two definitions, commonly reporting flight height as ‘jump height’ (Balsalobre-Fernández et al., 2015; Balsalobre-Fernández, Tejero-González, del Campo-Vecino, & Bavaresco, 2014; Magnúsdóttir, Porgilsson, & Karlsson, 2014; Wright et al., 2011). It is an important point to consider when comparing the studies that report the variable JH, as potential differences observed between studies maybe as a result of the use of an overestimation of one method compared to another method or how the variable JH is defined.

2.3.3. Linear Position Transducer Method

A linear position transducer (LPT) is a device for measuring a displacement-time history of a participant. The two most commonly used LPTs are the Tendo Fitrodyne Powerlizer (Fitro-Dyne; Fitronic, Bratislava, Slovakia) and the GymAware Power Tool (Kinetic Performance Technologies, Canberra, Australia). The Tendo and GymAware unit consist of either a rotary encoder or a digital optical encoder with retractable cord that is wound around a slotted disk with a linear sensor unit and microcomputer. The other end of the retractable cord is attached to a fixed position on a participant or a barbell. For assessing a CMJ the cord is attached at waist height, attempting to measure the participant's displacement of the CoG. When a participant performs a CMJ this would to initially cause the cord to wind around the disk during the countermovement then to unwind during the propulsive phase of the jump. A displacement-time history is then measured using a signal driven sampling scheme (Mian Qaisar, Fesquet, & Renaudin, 2009).

Limited data has been reported with regards to a LTP measuring a bodyweight CMJ. The majority of research has investigated weighted jumps or weighted weightlifting movements with the cord attached to a barbell, rather than attached to the waist (Cormie, McCaulley, & McBride, 2007; Hori, Nosaka, McGuigan, & Newton, 2006; Li, Olson, & Winchester, 2008; Mundy, Lake, Carden, Smith, & Lauder, 2016; Mundy, Smith, Lauder, & Lake, 2016). Furthermore, a number of issues arise with when using the LTP to measure CMJ and jump performance. Firstly, the LTP does not measure the displacement-time data of the jumper's CoG as when a CMJ is performed the CoG will move position whereas the fixed attached point of the cord will not follow the change in position of the jumpers CoG. Consequently, the attained displacement-time history may not reflect the actual displacement of the CoG (Hori et al., 2007; Lake, Lauder, & Smith, 2012; Li et al., 2008). Though not reported in terms of measuring a bodyweight CMJ previous research has identified that when the cord is attached to a barbell to measure a weighted CMJ, if there is horizontal movement by 10 degrees the velocity-time history derived from the displacement-time history would overestimate vertical velocity by 1.39 $m.s^{-1}$ (Mundy, Lake, et al., 2016). Lastly, a significant issue arises in terms of data manipulation of the displacement-time history, in order to attain variables such as velocity, acceleration, force and power. To attain variables such as velocity the displacement-time history must be differentiated, which will result in an amplification of noise in the velocity-time signal (Mundy, Lake, et al., 2016). As such this method requires further data manipulation known as filtering which introduces potential error due to over or under smoothing and degradation of the true signal (Mundy, Smith, et al., 2016). To attain acceleration data this process must be repeated (double differentiation and double filtering), which will further introduce noise and removal of the true signal. Subsequently, other derived variables such as force and power may not actually represent what is happening in the movement due to excessive data manipulation (Garnacho-Castaño, López-Lastra, & Maté-Muñoz, 2014). For example, erroneous errors observed from the velocity-time history attained from a weighted jump in a CMJ measured via a LTP could be a reason for the significant differences observed between the criterion force platform method and LTP method for measuring PPO for the same jump (Mundy, Lake, et al., 2016).

2.3.4 Force Platform Method

The force platform method (FPM) was first introduced by Davies & Rennie, (1968) for the measurement of mechanical power in vertical jumping. The FPM is now considered the criterion method for measuring vertical jumping performance and subsequently CMJ performance. A criterion method is considered to be a reference method that is generally accepted to be the most valid method of measuring a given variable or outcome. The FPM collects a ground reaction force-time history which is comprised of 3 components: the vertical component (VGRF), anterior-posterior component (Fy) and medial-lateral component (Fx). The FPM can measure a wide variety of CMJ neuromuscular performance variables such as JH, peak force (Fmax), rate of force development (RFD), velocity, and PPO (Harman, Rosenstein, Frykman, & Rosenstein, 1991; Hatze, 1998; D. L. Johnson & Bahamonde, 1996; Kibele, 1998; Lara, Abián, Alegre, Jiménez, & Aguado, 2006; Owen et al., 2014; Sayers et al., 1999). Neuromuscular variables such as PPO, JH and velocity are derived mathematically from the VGRF-time history. As a result the FPM is by far the most sophisticated method for determining CMJ performance variables, and subsequently requires its own section (Section 2.4) to discuss the key factors and limitations associated with this method.

2.4 The Force Platform as an Instrument for Assessing Neuromuscular Performance in Countermovement Jump

In the study of human movement a force platform (FP) is a device that measures the ground reaction force-time histories in three orthogonal dimensions (vertical and two horizontal). A FP is a metal or composite platform instrumented with four force transducers, one in each corner (Figure 2.4.1). A force transducer is a device that converts a force applied to the FP into some other physical quantity which in turn is converted into a voltage signal proportional to the applied force. Each of the four transducers is comprised of three individual transducers for each orthogonal direction and is constructed such that any force applied to it is transmitted to the ground through the transducers (Owen, 2008). Only the vertical component of the ground reaction force (VGRF) will be discussed, however, the principles are the same for the other directions.

Figure 2.4. 1. A 9260AA6 Model Kistler force platform showing the four force transducers in each corner of the force platform. Courtesy of Kistler UK

There are 3 main types of force transducer commonly used in the construction of FPs: 1) Piezoelectric: piezoelectric transducers are manufactured from naturally occurring quartz crystal. The transducer is designed such that any applied force acts directly on the crystal which responds by converting the applied force into an electrical charge. The resulting charge is proportional to the applied force (Owen, 2008); 2) Strain gauge: strain gauges consist 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 (Owen, 2008); 3) Hall Effect sensors: Hall Effect sensors are semiconductor devices that are sensitive to magnetic fields, in terms of devices conductance. If a magnet were placed on a mechanical spring such that an applied force altered the magnet's 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 (Owen, 2008).

Transducers in general and specifically force transducers (Table 2.4.1) do not produce signals that are directly compatible with a digital computer and as a result additional signal conditioning equipment is necessary in order to achieve an appropriate interface (Pohlmann, 2010). Each characteristic quantity produced by a transducer is first converted into a voltage, proportional to the original signal. The voltage is then converted into a digital signal, via an analogue to digital (A to D) converter. When the signal is in digital form it can be processed, displayed and recorded, using specialized software by a computer. In a FP the total VGRF is the arithmetic sum of the output of the four individual vertical transducers. The summation of the VGRF would be carried out within the computer as all transducer signals are usually input to the computer individually.

Table 2.4. 1. Different types of force transducers. Adapted from Owen. (2008)

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})

2.4.1 Limitations in Research Using Force Plates to Assess Jumping

Though a countermovement jump (CMJ) performed on a FP is the criterion method for measuring lower limb neuromuscular performance (Davies & Rennie, 1968; Owen et al., 2014). To mathematically derive common performance testing variables such as power, displacement and velocity from the force-time history of a CMJ, integration must be performed. However, there are a number of key sources of error associated with this method that must be addressed. The primary factors that contribute to random and systematic error being accumulated during a jump have been identified as: the sampling frequency, resolution of the force platform, selection of the vertical force range, chosen method of measuring bodyweight and identification of the start of the jump and the start of integration (Hatze, 1998; Kibele, 1998; Owen et al., 2014; Street, McMillan, Board, Rasmussen, & Heneghan, 2001; Vanrenterghem, De Clercq, & Van Cleven, 2001).

2.4.1.1 Sampling Frequency of the Force Platform

A FP system can only measure force values at certain (regular) time intervals, not continuously. The number of times a force values is 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 FP can be pre-selected, usually from 10 Hz to 2 kHz. In between sample points no information is known. Therefore, it is important to choose a sampling rate that is high enough to provide an accurate force-time history in terms of temporal events. For example, when comparing the same CMJ force-time (F/T) histories sampled at 1000 Hz and resampled at 10 Hz, the shapes of the two F/T histories appear similar for both sampling frequencies however perceivable difference are clear with details missing for the 10 Hz force-time (F/T) history (Figure 2.4.2). While the appearance of the bimodal peak force values at 0.6 s and 0.8 s on the 1000 Hz F/T history is missing on the 10 Hz F/T history which is represented as a straight line between these time points. The reason for the observed differences in the F/T history is because the forces involved in performing a CMJ change rapidly and a sampling rate of 10 Hz is insufficient to accurately reflect the true force-time history, as any changes in force that occur between sample points are effectively invisible to the FP system.

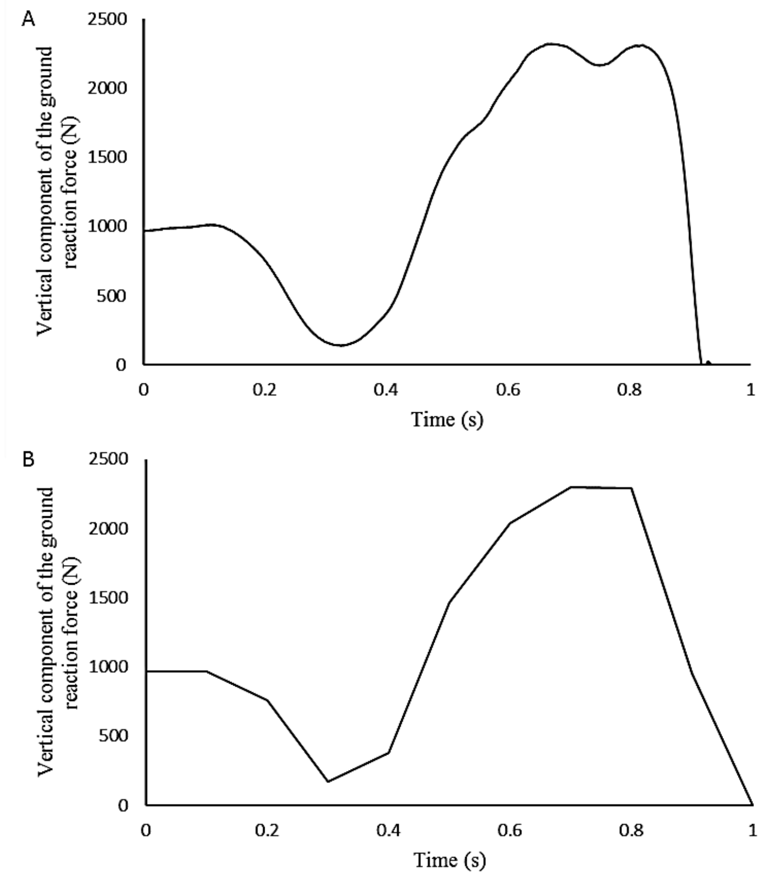

Figure 2.4. 2. Vertical component of the ground reaction force-time history for a countermovement sampled at A = 1000 Hz and B = 10 Hz

When sampling a signal the higher the sampling frequency the greater the fidelity of the representation of the original signal. Specifically, Nyquist's sampling theorem (Nyquist, 1928) states that a sampling frequency of at least double the highest frequency contained in the signal is necessary to ensure that none of the original signal is lost during the sampling process and also to prevent aliasing. The signal of interest in this thesis was the F/T history of a CMJ. Usually Fourier, analysis is used to determine the highest frequency present in a signal. However, a CMJ force-time history cannot be represented by a function as it is non-cyclical and as such is not suitable for this type of analysis. Several authors have recommended that the sampling frequency of a CMJ measured from a FP should be 1000 Hz (Kibele, 1998; Linthorne, 2001; Owen et al., 2014; Street et al., 2001; Vanrenterghem et al., 2001). Though some FP systems can sample up to 2000 Hz as reported by Hatze. (1998), it was not recommended in the criterion method measuring instantaneous lower body peak mechanical power as there is no there is no differences between 2000 Hz and 1000 Hz, therefore there would be no need to sample at 2000 Hz because a sampling frequency of 1000 Hz would achieve precision of <1% (Owen, 2008; Owen et al., 2014). In addition, an unnecessarily high sample rate will increase the cost and accessibility of equipment in addition to the amount of data generated and use more computer memory for storage than is necessary, resulting in the analysis taking longer than it otherwise would especially if it was analysed using a spreadsheet (Owen, 2008).

2.4.1.2 Resolution of the Force Platform

A FP has a very large dynamic range from <10 N to many 10,000's N. However, there are limitations within the analogue to digital converters which restrict the resolution of the system. Analogue signals, that can vary infinitely, are represented digitally as a series of discrete values; that is they can only take certain 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 (Pohlmann, 2010). For example, a 2 bit binary number can represent 4 discrete values (2^2), whereas a 3 bit binary number can represent 8 discrete values (2^3). If a 2 bit binary number was representing a 0 to 200N scale then only 4 different values namely 0, 66, 132 and 198 N could be represented. Therefore, a force of 44 N would have a value of 66 N if represented by a 2 bit digital number and a value of 57 N if represented by a 3 bit digital number (Pohlmann, 2010). If the number of bits representing an analogue signal increases then so does the resolution, however, if the range of the signal increases then the resolution decreases. The two most common resolutions currently in use are 12 bit and 16 bit. A 12 bit ADC is capable of representing an analogue signal as 4,096 that is 2^{12}, discrete steps, and theoretically representing an analogue force signal range of 0-20 kN in discrete steps of 4.9 N, whereas a 16 bit (2^{16}) or 65,536 discrete levels would theoretically represent the same signal with a resolution of 0.3 N. In practice the resolution of a system is dependent on other factors in addition to ADC bits including system noise and actual force range as opposed to stated maximum range of the platform (Pohlmann, 2010). It is reasonable to expect a 16-bit ADC to better represent an analogue signal than a 12-bit ADC, therefore, a 16-bit ADC should be used in preference when high force ranges are used, with the absolute range of platform should be also clearly stated (Owen et al., 2014).

2.4.1.3 Selection of the Vertical Force Range

A FP will normally have a number of ranges such that lower ranges, for example ± 1 kN 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. Accurate determination of what range to use is crucial in producing an accurate force-time history. As stated a FP is comprised of four individual force transducers, one in each corner of the FP and the total force is the sum of each transducer to its respective component (i.e. vertical component of the ground reaction force). Consequently, it is necessary to determine the maximum force measured by each individual force transducers as the VGRF, in a CMJ will be different in for each force corner transducer unless the applied force is in the exact geometrical centre of the FP (Owen, 2008; Owen et al., 2014). Kibele. (1998) demonstrated that the maximum VGRF during a CMJ was in the region of 3 - 3.5 time's BW, but the individual vertical corner transducer loads were not reported. In contrast, Owen et al. (2014) considered the range of the individual force transducers, because if these are exceeded this will lead to errors in the measurement of the VGRF. For example, if the total vertical force range was set on the basis of 3.5 times the BW of the heaviest participant (1166 N) this would correspond a maximum expected vertical force of 4081 N, set on the base of 1020 N for each corresponding force transducer (4081 N/4) (Owen et al., 2014). Consequently, this value would have been exceeded in 1 or more corner force transducer in 47% of the jumps, resulting in an erroneous force reading. An error of this sort would not initially be obvious from the resultant vertical force record because an overloaded corner force transducer sensor would either produce a seemingly correct force-time history but out of the calibrated range or if the absolute maximum of the transducer had been reached a plateaued force-time history (Owen, 2008; Owen et al., 2014). In both cases when the individual force outputs had been summed the error would not be apparent (Owen, 2008; Owen et al., 2014).

2.4.1.4 The Chosen Method of Measuring Bodyweight

The determination of BW is critically important as the impulse-momentum method is very sensitive to the correct BW determination as an input variable, (Cormie, McBride, & McCaulley, 2007; Vanrenterghem et al., 2001) as BW is used to determine net force and attain body mass which is subsequently used to derived a number of variables such velocity, displacement and power therefore any errors in bodyweight will result in drifting and errors of these output variables. For example, a study by Street et al. (2001) who investigated the sources of error associated with calculating jump performance via the ground reaction force data found that a small error of 0.13% in BW resulted in the accumulation of 3.3% error in JH when using integration. It has previously been recommended, in order to minimise this error that a stationary phase of up to or above 1.5 seconds or 15000 samples should be applied prior to the jump to enable average value of BW. However, few studies have described this within their methodology, and some have recorded a BW as a mean of 44 samples or 0.044 seconds (Moir, Sanders, Button, & Glaister, 2005) to a mean of 4000 samples or 4 seconds (Buckthorpe, Morris, & Folland, 2012). The current criterion method as proposed by Owen et al. (2014) indicates that BW is taken to be the mean value of the vertical component of the ground reaction force during a 1 second period of quiet standing during the stance phase immediately before the signal to jump is given. The value produced by this method is then divided by acceleration due to gravity to express body mass (kg).

2.4.1.5 The Identification of the Start of the Jump/ Integration

One of the most important steps in analysing a F/T history of a CMJ is identification of the initiation of the jump. The initiation of the jump is essential in facilitating reliable and valid CMJ neuromuscular performance variables such as impulse, velocity, and mechanical power. In order to derive these variables numerical integration must be performed, which utilises the impulse-momentum, however when impulse is divided by body mass, to derive change in velocity, this only attains instantaneous values and therefore a start time is needed for the accumulation of values to determine the overall velocity at the particular sampled time point. Failure to do so can increase the degree of random and systematic error encountered (Street et al., 2001; Vanrenterghem et al., 2001). An assumption required is that the velocity of the whole body's centre of gravity (CoG) is zero just prior to the initiation of the jump. This is essential for the accumulation of instantaneous values. If the initiation of the jump is identified at the wrong time point this will result in a drifting of accumulated values resulting in an erroneous error of the derived velocity variable and subsequently other variables such as mechanical power and JH (Owen et al., 2014; Street et al., 2001). In practice the initiation of a jump is difficult to identity as a flat steady force-time history is not observed when analysing a CMJ. Natural variation of bodyweight just prior to a participant performing a CMJ is due to system noise and slight vertical oscillation of the CoG due to breathing and pendular swing of the CoG over the feet in order to actively maintain balance (Owen, 2008). Therefore, a method of determining the initiation of the jump that is sensitive to the changes outside of human variation is essential.

A recent systematic review highlighted a number of different methodologies used to determine the start time of the CMJ (Eagles, Sayers, Bousson, & Lovell, 2015). Three main studies were identified. The first method classifies the initiation of the jump as a 5% reduction in the vertical component of the ground reaction force (VGRF). This method was cited 96 times in the literature by a number of different authors (Eagles et al., 2015). The second and third method defines the start of the jump as the point when the VGRF exceeds a quiet standing value for the participant (typically a value 10 N). The second and third methods have been cited 256 times by a variety of authors (Eagles et al., 2015). There are significant limitations when using these methods to identify the start phase of the jump, for example if the second and third method identifies the initiation of the start of the jump when the VGRF exceeds 10 N in a 1000 N participant, this would represent only 1% of the participant's assumed BW from the VGRF during quiet standing, and the likelihood of a false start would be significant. In contrast, if the first method (reduction of 5% of BW) was used and a participant weighed 600 N, a 5% reduction would be 30 N and this might not be sensitive enough to highlight the exact point of the start time. One mayor limitation of all of the three methods is that they do not consider if VGRF increase at the start of the jump, this would identify the wrong start time for 50% of participants as demonstrated by Owen et al. (2014).

Figure 2.3.3 illustrates the same a CMJ force-time history with two different start times, the impulse is represented the net force and time data, which is the area below or above the force-time history and bodyweight line. Figure 2.3.3A illustrates a start time which only considers the start of the jump being initiated when there is a decrease in the VGRF for example method 2 and method 3 as descried previously by Eagles et al. (2015). This has resulted in part of the positive impulse being cut off, which consequently means there is a larger negative impulse during the eccentric phase, as a result a larger positive impulse is needed during the eccentric phase in order for the impulse to be equal. This has resulted in a longer eccentric phase, meaning that the eccentric to concentric (E-C) time point has occurred later than if the start time was identified correctly. This has resulted in a smaller concentric positive impulse causing a decrease in the variables velocity, displacement and mechanical power. Whereas, Figure 2.3.3B illustrates a CMJ with an initiation start time that only considers the start of the jump occurs from a decrease in the VGRF but is also not sensitive to have for example method 1 as descried previously by Eagles et al. (2015). This has resulted in part of the positive and negative impulse being cut off, which consequently means there is a smaller negative impulse during the eccentric phase, as a result a smaller positive impulse is needed during the eccentric phase in order for the impulse to be equal. This has resulted in a shorter eccentric phase, meaning that the eccentric to concentric (E-C) time point has occurred earlier than if the start time was identified correctly. This has resulted in a larger concentric positive impulse causing an increase in the variables velocity, displacement and mechanical power.

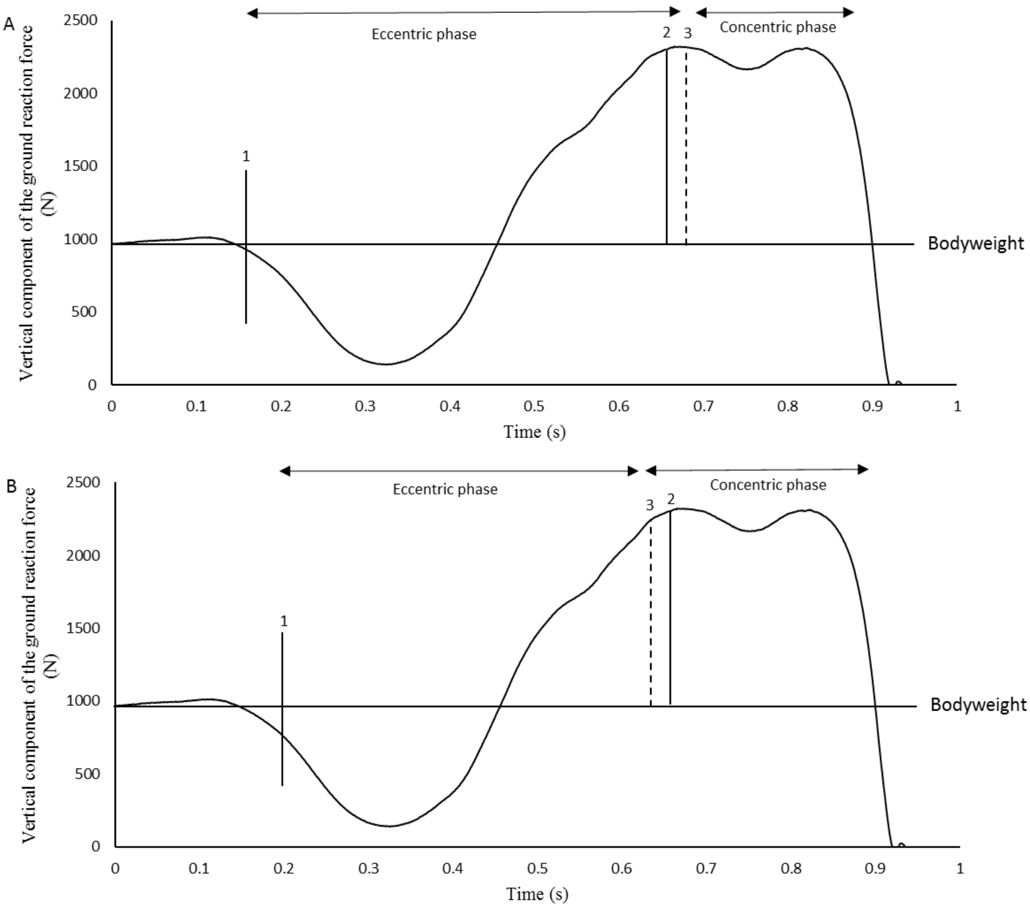

Figure 2.4. 3. The effect of miss-identifying integration start time of a countermovement jump

1 = incorrect integration start time, 2 = the eccentric concentric change over time point if start time was identified correctly, 3 = the new eccentric to concentric change time point from a start time identified incorrectly.

A major limitation of the review by Eagles et al. (2015) in determining the start time of the CMJ was not including the developed criterion method of Owen et al. (2014). This would have been the fourth method of phase identification as a comparison against a neutral data set. The reason the criterion method was not included in the search criteria was due to the title of the publication suggesting it was only for the development of a criterion method to determine peak mechanical power output in a CMJ and not jump height (JH). However, the same process is needed to identify the start of the jump prior to using numerical integration to determine instantaneous velocity which is then used in conjunction with force to derive mechanical power. The use of BW ± 5 SD significantly reduces the chance of a false start as it encompasses 99.999999% of the quiet standing force-time history and would only miss-trigger (an incorrect identification of “not quiet standing”) in 1 in 1744278 trials (Owen, 2008; Owen et al., 2014). Therefore, any change outside this would highlight the phase identification of the start of a CMJ. However, this method is population specific and would potentially need to be re-evaluated for other populations such as children.

2.4.2 Countermovement Jump Force-Time History Variables Used to Assess Athletic Performance

There have been numerous studies investigating CMJ neuromuscular performance in elite athletic populations and its association with fatigue and recovery (Bobbert & Casius, 2005; Hay, 1992; T. Taylor et al., 2015; West et al., 2013, 2014), monitoring the effectiveness of training (Soriano, Jiménez-Reyes, Rhea, & Marín, 2015; Wilson, Newton, Murphy, & Humphries, 1993), and distinguishing athlete competition level (Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008). The following section will discuss some of the most common CMJ neuromuscular variables reported within the literature that are measured via a FP.

2.4.2.1 Jump Height

The most frequently reported variable for assessing performance in a CMJ is JH (Chatzinikolaou et al., 2010; Oliver, Armstrong, & Williams, 2008; Sparkes et al., 2018; Taipale & Häkkinen, 2013; T. Taylor et al., 2015; Thorlund, Michalsik, Madsen, & Aagaard, 2008). Jump height has been found to correlate significantly with sprint performance (Cronin & Hansen, 2005), playing standard (Gabbett, 2009) and squad selection (Sawyer, Ostarello, Suess, & Dempsey, 2002). Previous research has highlighted the use of JH as an estimate of fatigue following competition and exercise (Oliver et al., 2008; Thorlund et al., 2008). In contrast, other studies have found there is no change in JH from protocols aimed at inducing fatigue when compared to baseline JH values (Cormack et al., 2008; Hoffman, Nusse, & Kang, 2003; Thorlund, Aagaard, & Madsen, 2009). It has been suggested that either the protocols used to induce fatigue were not adequate in terms of suppressing the neuromuscular system, or that use of JH is not sensitive to change from fatigue inducing exercises due to the a change in jump strategy observed under fatigued conditions (Cormack, 2008; Thorlund et al., 2008).

The term "change in jump strategy" refers to the ability to achieve the same JH score via different force-time characteristics when fatigued. The change in jump strategy may compensate for a sub-optimal ability to generate force to attain the same take-off velocity at the initiation of take-off which will enable the maintenance of the height jump when not under fatigue conditions. The change in the force generation would not be detected or reflected by the variable JH (Ugrinowitsch, Tricoli, Rodacki, Batista, & Ricard, 2007). Therefore, other variables such as Fmax (Gonzalez-Badillo & Marques, 2010; Sheppard, Doyle, & Taylor, 2008), RFD (Knudson, 2009; Nibali, Tombleson, Brady, & Wagner, 2015), and PPO (Cook, Kilduff, Crewther, Beaven, & West, 2014; Cunningham et al., 2013; Owen et al., 2014) are suggested to be better measures of neuromuscular function, fatigue and performance. For example Figure 2.4.4 highlights two different impulse-time histories with the same JH value taken from the same a participant performing two CMJs under a fatigued and non-fatigued condition. The impulse-time history of the baseline CMJ (solid line) and it subsequent JH and peak mechanical power output values (PPO). In contrast, the fatigued CMJ (dotted line) illustrates a greater eccentric time and negative impulse. Subsequently, in order to balance the negative impulse taken over a longer period of time, a greater positive impulse is required, again increasing the time taken from the baseline CMJ. However, as JH is not time dependent, the same value can still be achieved but just over a longer period of time. The variable PPO is time dependent, and therefore identifies the differences observed in the baseline CMJ versus the fatigued CMJ.

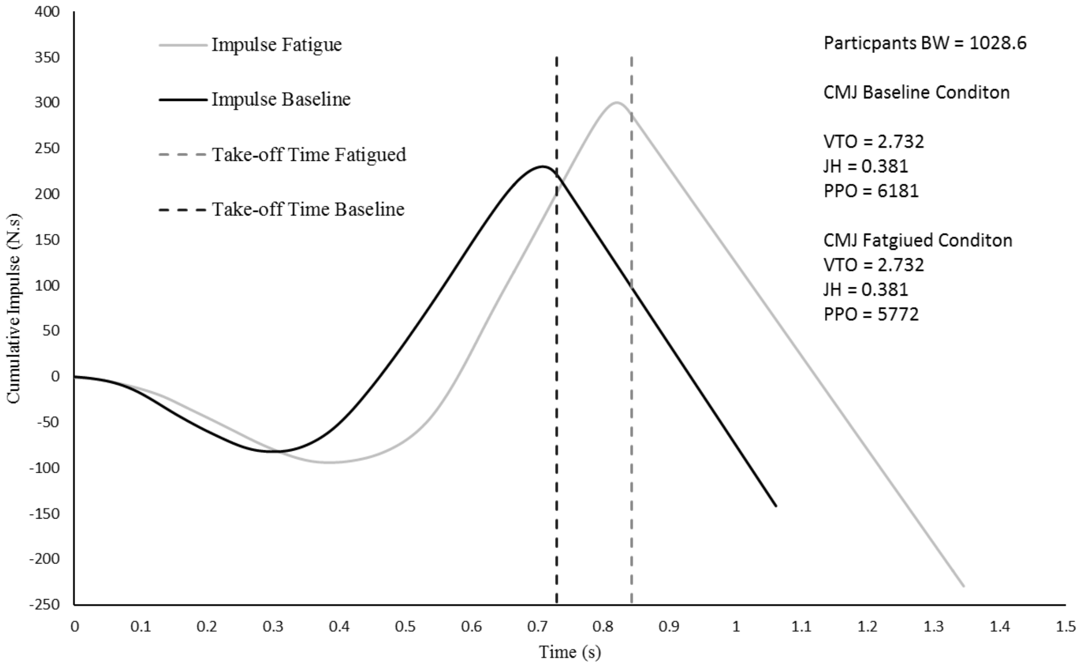

Figure 2.4. 4. Change in jump strategy for an impulse-time history and its corresponding take-off velocity, jump height and peak power output values.

Where BW = bodyweight (N), CMJ = countermovement jump, VTO = velocity of the centre of gravity at take-off (m.s^{-1}), JH = jump height (m) and PPO = instantaneous peak mechanical power (W)

2.4.2.2 Peak Force

Peak force (Fmax) is defined as the muscles ability to generate maximal force at a specified or determined velocity (Komi, 1992). The ability to generate high levels of Fmax has been associated with enhanced force-time characteristics such as rate of force development and peak mechanical power output (Suchomel, Nimphius, & Stone, 2016), sensitivity to detect changes in performance levels as a result of training (Sheppard, Cormack, et al., 2008), monitoring fatigue during competition (Hoffman et al., 2002), performance of activities of daily living (Maffiuletti et al., 2016; Tillin, Pain, & Folland, 2013), provide a surrogate measure of maturation status (Lloyd & Oliver, 2013), discriminate between athlete playing level (Sheppard, Cormack, et al., 2008) and reduction in injury rate (Suchomel et al., 2016). The measurement of Fmax can be measured through inspection of the CMJ force-time history and is taken to be the one sample with the highest numerical value of the VGRF during the sampling period of the F/T history. No data manipulation is needed for attaining Fmax, for example the variable does not require the identification of a start point (jump start and integration start) or any additional data processing, in way that is necessary for other measures like rate of force development (RFD) which requires filtering to remove noise. The measurement of Fmax is considered to be a key variable when assessing performance of a CMJ, due to its association with athletic performance and aspects of daily living.

2.4.2.3 Rate of Force Development

The term "explosive strength" is often defined as the ability to increase force or torque as quickly as possible during a rapid voluntary contraction from a low or resting level (Maffiuletti et al., 2016). Rate of force development (RFD) can be reported as either peak, average or the force at specific time points during an performance test (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). Peak RFD is defined as the greatest value of the first derivative of force with respect to time, whilst average RFD is defined as the mean value of the first derivative with respect to time (Moir et al., 2009). In a recent review on physiological and methodology considerations of RFD by Maffiuletti et al. (2016), highlighted that the ability to quantify and interpret RFD is extremely important as it has been closely linked to sport performance (Cormie, McGuigan, & Newton, 2010; Thorlund et al., 2009, 2008) and activities of daily living (Maffiuletti et al., 2016; Tillin et al., 2013). It is very sensitive in detecting acute and chronic changes in neuromuscular function, for example changes in jump strategy not observed in other measures such as JH and Fmax (Angelozzi et al., 2012; Crameri et al., 2007; Jenkins et al., 2014; Nibali et al., 2015) and potentially governed by different physiological mechanism (Andersen & Aagaard, 2006). There are very few studies within the literature that report RFD during a CMJ to measure neuromuscular performance (Bagheri, van den Berg-Emons, Pel, Horemans, & Stam, 2011; Jakobsen et al., 2012; Nibali et al., 2015; Thorlund et al., 2008).

The gold standard for measuring RFD is considered to from force collected in an isometric maximal voluntary contraction (MVC) as RFD is known to be influenced by muscle groups and joint angles (Bellumori, Jaric, & Knight, 2011; Tillin, Pain, & Folland, 2012). This may suggest why measured RFD in a CMJ studies had notably had poor reliability values with reported coefficient of variation (CV) for peak RFD of 36.4% (Sheppard, Cormack, et al., 2008), 35.5% (Moir et al., 2009), 17.9% (McLellan, Lovell, & Gass, 2011) and 24% (Hori et al., 2009) and average RFD 21% (Moir et al., 2009) and 21.3% (Nibali et al., 2015).

2.4.2.4 Peak Mechanical Power Output

Mechanical work must be performed to accelerate and or raise the CoG of the body during dynamic athletic tasks (Cavagna, 1975; Mundy, Smith, et al., 2016). Peak mechanical power output is widely considered to be a key determinant of athletic performance, particularly in sports that require large amounts of force generation and a high velocity in a short period of time (Cook et al., 2014; Cronin & Hansen, 2005; Cunningham et al., 2013; Kawamori et al., 2005; McGuigan, Cormack, & Gill, 2013; Mundy, Smith, et al., 2016; Owen et al., 2014; Soriano et al., 2015; Thorlund et al., 2008; West et al., 2011). Mechanical peak power output has previously been used to measure neuromuscular fatigue and recovery (Cook et al., 2014; West et al., 2014), monitor the effectiveness training (Soriano et al., 2015; Wilson et al., 1993), distinguish athlete competition level (Sheppard, Cormack, et al., 2008), weightlifting (Hori et al., 2006), and when normalised to body mass, a very high correlation to sprint performance is achieved (Cronin & Hansen, 2005; Cunningham et al., 2013). The criterion method of determining PPO from a CMJ using a FP is to evaluate the product of the VGRF and the vertical velocity of the CoG (Owen, 2008; Owen et al., 2014). Owen et al. (2014) reported errors of <1% when using this method to determine PPO.

2.4.3 Differences Between Adult and Children Countermovement Jump Force-Time History Variables

There is limited information currently available comparing children and adults with regards to CMJ performance measured via a FP. Although significant differences may be anticipated, it remains to be reported which parameters differ and the magnitude of difference. Indeed only six previous studies have investigated CMJ F/T history variables via a FP (Busche et al., 2013; Focke et al., 2013; Gabel et al., 2016; Sumnik et al., 2013), with only three study directly comparing children and young adults (Gabel et al., 2016; Raffalt et al., 2016b, 2016a). However, the findings of these studies remain largely unclear, due to a number of CMJ variables reported with limited to no information with regards how start time (t_s) or other important specifications are determined to prior to calculation of the CMJ variables. For example, Raffalt, Alkjaer

& Simonsen (2016b) demonstrated that jump height (JH) was significantly higher and less variable in 20 male adults when compared to 11 male boys, whereas allometrically scaled knee joint power and Fmax were greater in children. The results of this study are in accord with Focke et al. (2013) who demonstrated that JH increased with age whereas, relative Fmax and RFD decreased or remained constant. Furthermore, significant sex differences have been reported in children, with boys having significantly larger values for absolute JH and girls having significantly larger values for normalised Fmax and RFD. In contrast, Sumnik et al. (2013) and Busche et al. (2013) utilised jumping mechanography to provide reference data for absolute Fmax and PPO from a CMJ with arm swing highlighting that significant age effects occurred for PPO, JH and Fmax with no significant sex differences occurring until 12 years of age (Busche et al., 2013; Gabel et al., 2016; Sumnik et al., 2013). The reason for the discrepancies between these studies is presently unclear, however further interpretations are limited by certain methodological limitations such as the techniques used to attain unprocessed and processed F/T history CMJ variables. Specifically, Raffalt, Alkjaer & Simonsen. (2016b) utilised the CMJ variable JH which was derived via vertical velocity of the COG at take-off, calculated via numerical integration, yet no integration start time was defined or stated. In contrast, Focke et al. (2013) reported initiation time of the jump (also integration start time) yet the use of terminology and bodyweight (BW) thresholds to identify the initiation time of the jump used to subsequently measure JH lacked clarity. Additionally, the use of relative or absolute variables may account, at least in part, for the differences in findings as they have been used interchangeably throughout without rationale, further information with regards to accounting for body size in child populations is presented in Appendix V: Extension to Review of Literature. A variable that has been highlighted of particular importance in both adult and child populations is the variable mechanical power, therefore this variable and the method in which to achieve it will be discussed extensively in Section 2.5.

2.5 Criterion Method of Determining Peak Mechanical Power and Other Processed Variables

Attempts to measure mechanical power produced by the legs in a vertical jump date back to Sargent (1924) who proposed that the product of height jumped performing a vertical jump and a participant's weight, normalised to stature was an estimated measure of leg power. Over forty 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 potentially energy during the propulsion and flight phases in a jump and reach test. However, though the formula presented the correct physical units it was limited by assumptions that there was no relative motion between the whole body centre of gravity (CoG) 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 CoG 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. The vertical acceleration of the CoG is directly proportional to the vertical component of the ground reaction force (VGRF) and therefore, has the same shape time history as the VGRF-time history which reveals that the acceleration is clearly non-uniform. Though the vertical power jump of Gray et al. (1962) provides an estimate of average leg power, Davies & Rennie. (1968) proposed a method of measuring instantaneous vertical mechanical power output of a countermovement jump (CMJ) by means of a force platform (FP). The FP method of measuring instantaneous mechanical power has become the accepted method when evaluating vertical jumps (Canavan & Vescovi, 2004; Harman, Rosenstein, Frykman, Rosenstein, & Kraemer, 1991; Hertogh & Hue, 2002; D. L. Johnson & Bahamonde, 1996; Lara et al., 2006; Owen, 2008; Sayers et al., 1999; Shetty, 2002). This method requires a participant to perform a vertical jump on a FP. The VGRF-time history of the jump is recorded and the force data is presented 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, therefore, numerical integration is utilised (Kibele, 1998). Numerical integration of the net force-time history divided by mass produces the instantaneous vertical velocity of the CoG. The corresponding instantaneous mechanical power for a time t, is given by the product of force and velocity at that time point.

$$P_t = F_t \cdot v_t$$

Equation 2

Where P_t = corresponding instantaneous mechanical power (W), F_t = corresponding instantaneous force (N), and v_t = corresponding instantaneous velocity ($m.s^{-1}$).

In order to determine instantaneous mechanical power from a CMJ via a FP, a number of specifications must be considered to reduce the sources of error. Seven specifications have been identified for the measurement of PPO which are: (1) the determination of body weight, (2) the selection of the vertical force range, (3) selection of the resolution, (4) the identification of the initiation of a CMJ, (5) the selection of the sampling frequency, (6) the integration frequency and (7) method of numerical integration (Owen et al., 2014). Previous research has investigated these specifications in order to reduce the amount of error when calculating PPO (Hatze, 1998; Kibele, 1998; Street et al., 2001; Vanrenterghem et al., 2001). However, each specification was investigated in isolation, previously discussed in section 2.4 and demonstrated in Table 2.5.1. The study of Owen et al. (2014), was the first to investigate the combination of all the specifications required for the accurate calculation of PPO, leading to the development of the criterion method to determine PPO and other variables from a CMJ via a FP in elite adults (Owen et al., 2014).

Table 2.5. 1. Specifications that affect accuracy and precision of velocity-time and displacement-time data derived from integrating force-time data. Adapted from Owen. (2008)

Recommended specification values or method of determining specification				
	Kibele. (1998)	Hatze. (1998)	Vanrenterghem et al. (2001)	Street et al. (2001)
Sampling frequency and resolution	1000 Hz at 12 bits	2000 Hz, resolution not considered	100 to 1000 Hz no single frequency was recommended, resolution not considered	1080 Hz, resolution not considered
Vertical force range	3-3.5 x BW of the highest participant	Not considered	Not considered	Not considered
Integration frequency	Not stated	2000 Hz	100 to 1000 Hz no single frequency was recommend	Not stated
Method of integration	Trapezoidal Rule	Not stated	Trapezoidal Rule	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	The average voltage for the first 2 s of the sampling period
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	Detected by searching for the 1st deviate above or below BW by more than 1.75 times the peak residual found in the 2s BW averaging period. A backwards search was performed until Fz had passed through body weight

The criterion measure of PPO produced in a CMJ (Table 2.5.2) uses the product of the VGRF and vertical velocity of the CoG via a FP system sampling at 1000 Hz with a force range of 5.6 x BW at a 16-bit resolution (Owen et al., 2014). To determine the instantaneous velocity of an individual's CoG, numerical integration (numerical integration sampling frequency 1000Hz) is performed using Simpson's rule with intervals equal to the sample interval of the vertical component of the ground reaction force (VGRF) during the CMJ (Hatze, 1998). The instantaneous velocity-time history is then integrated (double integration of the acceleration-time history) in order to determine displacement of an individual's CoG during a CMJ. Before integration can occur, the participant's body weight (as measured by the mean VGRF during the 1 second period of quiet standing prior to the signal to jump [stationary phase]) is subtracted from the VGRF values. Instantaneous values which is the area of the strip, with width equal to the sample rate, then represented the impulse for that time interval. Using the relationship that impulse equals change in momentum, the strip area is then divided by the participant's mass to produce a value for the change in velocity for the CoG (it is assumed that the participant's mass remains constant throughout the jump). The change in velocity is then added to the CoG previous velocity to produce a new velocity at an instant equal to that particular interval's end time, with this process continued throughout the jump. A similar process is used for the determination of displacement of an individual's CoG from the velocity-time history. As this method can only determine the change in velocity and change in displacement, it is necessary to know the CoG velocity at some point in time. For this purpose, the velocity of the CoG was taken to be zero before the initiation of the jump (during the period of body weight measurement), specifically at the point identified as the start of the jump.

Table 2.5. 2. Criterion method specification for the measurement of peak mechanical power in a countermovement jump by the criterion force platform method. A specification of BW ± five standard deviations as opposed to a reduction in BW for jump initiation was necessary as generally approximately half of all jumpers start a CMJ by first rising their centre of gravity. Adapted from: Owen et al. (2014)

Variable	Criterion method specification
Vertical force range and resolution	5.6 x BW or higher at 16 bit resolution
Sampling frequency	1000 Hz
Integration frequency	1000 Hz
Method of integration	Simpson's rule or trapezoidal rule
Determination of body weight	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	The instant that BW ± five standard deviations is exceeded after the signal to jump has been given minus 30ms

Note BW = Bodyweight

The identification of the initiation of a CMJ point was defined as the time when the participant's ground reaction force exceeded the mean ± 5 standard deviations from the values obtained in the 1 second (of the stationary body mass measuring phase) immediately before the command to jump, in a fashion similar to Vanrenterghem et al. (2001). Integration started from this point (Owen, 2008). Plus or minus 5 standard deviations was chosen as the start point due to variation in the measurement of the body weight of a participant at rest on a FP (Owen et al., 2014). This is due to system noise and slight vertical oscillation of the whole body CoG due to breathing and pendular swing of the whole body CoG over the feet in order to actively maintain balance (Owen, 2008). To identify when the body weight of the participant has changed beyond normal variation, a threshold level of normal variation needs to be established, plus or minus 5 standard deviations was chosen to reduce the probability of an erroneous initiation, $p = 2x10^{-9}$ (Owen, 2008). Instantaneous power can then be measured following the standard relationship:

$$P = F \cdot v$$

Equation 3

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

The method developed by Owen et al. (2014) for calculating PPO, impulse, velocity and displacement has been accepted within the field of sport science as the criterion protocol for measuring CMJ performance variables in elite adults via a FP. However, there appears to be no standard or accepted method for the collection of VGRF-time data and its subsequent analysis for children. Section 2.6 reviews the consequences of measuring PPO in children without consideration of a criterion method.

2.6 Measurement of Mechanical Power in Children

The measurement of mechanical power in non-sporting elite populations has become a substantial area of applied research. For example, researchers investigating child populations have or attempted to measure peak mechanical power output to identify a variety of factors such as relationship with overweight and obesity (Bovet et al., 2007), measuring bone strength and health (Schoenau & Fricke, 2008; Weeks et al., 2008), monitoring maturation status (Beunen & Malina, 2008), talent identification (Lloyd et al., 2015) and measuring coordination (Clark et al., 1989; Jensen, Phillips, & Clark, 1994; Korff et al., 2009). As mechanical power is increasingly being used as a metric in children, an appropriate method for its measurement which is valid and reliable is clearly important as previously discussed in Section 2.5 and Section 2.6. Whilst there is a published criterion method (Table 2.6.2) for measuring lower body instantaneous lower body peak mechanical power output (PPO) in elite adults (Owen et al., 2014), there appears to be no standard or accepted method for measuring PPO in children (Clark et al., 1989; Jensen et al., 1994). Furthermore, the cost and accessibility of specialist equipment such as a force platform needed to measure mechanical power has resulted in the use of estimates and surrogate variables, as a means of attempting to calculate PPO in children (Duncan, Hankey, & Nevill, 2013). However, many of these studies attempting to calculate PPO have not investigated whether they are valid, reliable or a suitable method for children (Duncan, Hankey, & Nevill, 2013; Knudson, 2009). A surrogate variable of PPO is when a different countermovement jump (CMJ) variable is used as a substitute to represent the measurement of PPO. The surrogate variable would typically be correlated or related to PPO in some way. One common surrogate variable of PPO attained from a CMJ is the variable jump height (JH) which can be measured with relatively inexpensive equipment (Balsalobre-Fernández et al., 2014; B. L. Johnson & Nelson, 1979; Sargent, 1924). However, limitations with the equipment's reliability, validity and JH is defined within the literature has previously been scrutinised (Nuzzo, Anning, & Scharfenberg, 2011). An estimation is a rough calculation of a value. Regression equations based on several "easy to measure" jump and participant variables are the most common form of estimating PPO. For example, the variables most frequently used in regression equations to estimate PPO from a CMJ are the participant's mass, standing height and JH. This would subsequently output an estimated value of PPO (Canavan & Vescovi, 2004; Harman, Rosenstein, Frykman, Rosenstein, et al., 1991; Hertogh & Hue, 2002; D. L. Johnson & Bahamonde, 1996; Lara et al., 2006; Sayers et al., 1999; Shetty, 2002). A number of regression equations have been presented for the estimation of PPO; however, the validity of the results of these regression studies are not clear (Canavan & Vescovi, 2004; Harman, Rosenstein, Frykman, Rosenstein, et al., 1991; Hertogh & Hue, 2002; D. L. Johnson & Bahamonde, 1996; Lara et al., 2006; Sayers et al., 1999; Shetty, 2002). Therefore, the following sections will review the various surrogate, estimates and measurements of power in children.

2.6.1 The Use of a Surrogate Variable to Represent Mechanical Power in Children

The most common variable used to assess the natural development of maximal muscular power is JH (Harrison & Gaffney, 2001; Isaacs, 1998). There are many limitations associated with the use of using JH as an indirect measures to assess power such as the validity and reliability of the equipment (M. J. D. Taylor et al., 2010). Nerveless, the CMJ variable JH has been used and defined as the measurement of "muscular power" in children with regards to monitoring the development of the neuromuscular system throughout childhood. With regards to this subsection (2.6.1) the term "power" or muscular power" reported within the literature is actually the variable JH attained from the jump and reach method. The pattern of coordination required for jumping is usually developed between 3 and 4 years of age with the fully mature pattern (coordination and control) being achieved by 6 years of age. Previous research has indicated that there exist periods of rapid development in power (jump and reach height) between the ages of 5 and 10 years (Borms, 1986; Branta, Haubenstricker, & Seefeldt, 1984; Viru et al., 1999) with no significant differences observed between sexes up to the age of 11 (Temfemo, Hugues, Chardon, Mandengue,

& Ahmaidi, 2009). A secondary spurt in power (jump and reach height) was established between the ages of 9 and 12 years in girls and 12 and 14 years in boys (Beunen, 1988; Branta et al., 1984; Haubenstricker & Seefeldt, 1986). This development phase occurs in accordance with the onset on puberty (Ford et al., 2011), and owing to the differential maturation rates between boys and girls, clear significant sex differences exist and can be seen from the ages of 14 onwards as seen in Figure 2.6.1, with boys making significantly greater gains in muscular power (jump and reach height) when compared to girls (Beunen, 1988; Branta et al., 1984; Focke et al., 2013; Haubenstricker & Seefeldt, 1986; Martin et al., 2004; M. J. D. Taylor et al., 2010; Temfemo et al., 2009).

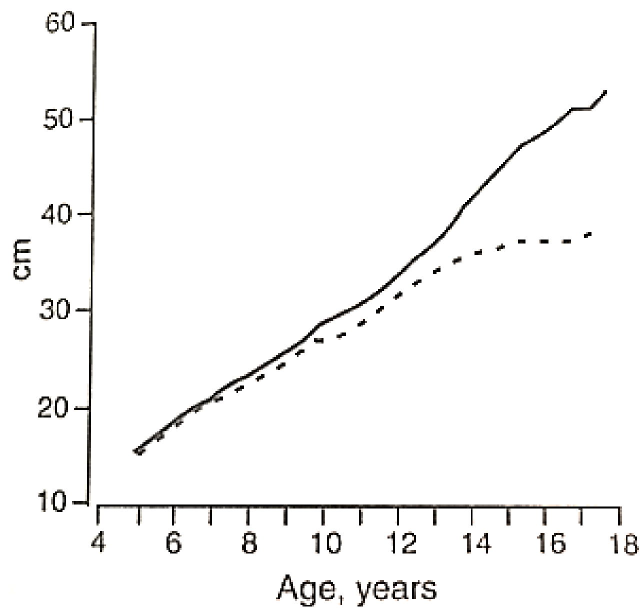

Figure 2.6. 1. Mean performance of vertical jump and reach score between 5 and 18 years of age of boys (black line) and girls (dotted line). Source: Haubenstricker and Seefeldt (1986)

2.6.2 Estimates to Assess Mechanical Power in Children

The use of estimates to assess mechanical power output from a CM refers to the use of other more easily measured variables such as body mass, stature and JH which does not require highly expensive and less readily available laboratory equipment (Owen, 2008). A summary of the regression equations established in the literature for estimating mechanical power output from a vertical jump for various populations, including children is summarised in Table 2.6.1 (Canavan & Vescovi, 2004; Duncan, Hankey, Lyons, et al., 2013; Duncan, Hankey, & Nevill, 2013; Harman, Rosenstein, Frykman, Rosenstein, et al., 1991; D. L. Johnson & Bahamonde, 1996; Lara et al., 2006; Sayers et al., 1999; Shetty, 2002).

Table 2.6. 1. Summary table of the current regression equations used to measure peak power. Adapted and Updated from: Owen. (2008)

Author (type of jump)	Regression Equation (Peak or Average Power)	Criterion Mean Power Results (W)	Regression equation mean power Results (W)	Participants	Description of Criterion method	Predictor Jump Method
Fox and Mathews. (1974) Lewis formula[1] (not stated)	P = 9.8√(4.9).(M).√(H) (not stated)	NA	NA	NA	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)	17M (age = 28.5 ± 6.9, mass = 74.7 ± 7. y kg)	Force platform 500 Hz, Pi = F.v Integrated at 20 Hz	Jump and reach
Johnson and Bahamonde . (1996) (CMJ)	Pp = 785(H) + 60.6(M) - 15.3(S) - 1308	4707	4687 (R^2 = 0.91, SEE = 462W)	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, Pi = F.v	Jump and reach

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= 561.5W)	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)	P = -666.3 + 14.74(M) + 1925.72(H) (not stated)	1458	1451 (R^2 = 0.69 ($p < 0.05$), S.D. = 222W)	19M untrained (age = 20.9 ± 1.3 yrs, mass = 78.9 ± 12.3 kg)	Force platform, 100 Hz, Pi = F.	Jump and reach
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 = 120.8W)	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) (CMJ)	Pp = 625(H) + 50.3(M) - 2184.7 (peak power)	3524	3624 (no sig. diff. ($p < 0.05$) SEE = 246.5W)	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

Quagiarella et al. (2011) (CMJ)					Force platform (Kistler), 1000 Hz, method – Matlab custom software	Jump height determined via flight-time method
Amonette et al. (2013) (CMJ)	Overall Pp (1) = (63.6 3 VJH) + (42.7 3 BM) - 1,846.5 12 -15 y Pp (2) = (61.9 3 VJH) + (40.8 3 BM) - 1,680.7 16-18y Pp (3) = (63.6 3 VJH) + (46.2 3 BM) - 2,108.2 19+ y Pp = (83.0 3 VJH) + (54.5 3 BM) - 3,436.8	3244	(1) = 3252 (R^2 = 0.92, SEE = 250.7 W) (2) = 2366 (R^2 = 0.92, SEE = 232.6 W) (3) = 3818 (R^2 = 0.83), SEE = 258.2 W) (4) = 3605 (R^2 = 0.84, SEE = 277.9 W)	(1) = 415M Athletes (age = 15.4 ± 2.6 years, mass = 65.1 ± 14.8 kg) (2) = 24M Athletes (age = 13..4 ± 2.6 years, mass = 65.1 ± 14.8 kg)	Force platform (Labview 7.1 and Dart power), 400 Hz, method – custom script Matlab software.	Jump height determined CoG velocity via ground reaction force
Duncan et al. (2013) (CMJ)	PP_{est} ¼ a_1 þ $b_1$3_CMJ height_ þ $c_1$3_body mass_ PP_{est} ¼ $a_2$3_CMJ			77 (62 M, 15 F, age = 16.8 ± 0.8 years, mass =74.6 ± 10.7 kg, height 1.82 ± 0.10 (m)	Force platform , 500 Hz, method - Quattro Jump (Kistler)	Jump height determined by Quattro Jump - not defined

	height_b 23_body mass_c 2					
Duncan et al. (2013) (CMJ)	Pp = –2732.5 + (309.2 × boys) + (110.6 × age) + (35.5 × body mass) + (38.4 × CMJ height) (peak power) Pp = 3.717 × (1.108 × boys) × exp (0.054 × age) × body $mass^{0.829}$ × CMJ $height^{0.636}$	2452.8		91 (40 M, 51 F) school children (age = 14.3 ± 1.3 years, mass = =53.4 ± 11.4 kg, height = 1.60. ± 0.10 m	Force platform , 500 Hz, method - Quattro Jump (Kistler)	Jump height determined by Quattro Jump - not defined

Note: H = height jump (m), Pp = peak power, M = male, F = female, S = stature, SE = standard error, CMJ = countermovement jump, CoG = centre of gravity, P = power, SJ = squat jump, R^2 = coefficient of determination, SEE – standard error of estimate, r = correlation coefficient, [1] the Lewis formula is not a regression equation but has been used as such in numerous previous studies and is therefore, included for completeness

Previous research has however, questioned the validity of these existing range of PPO estimation equations (Canavan & Vescovi, 2004; Duncan, Hankey, & Nevill, 2013; Knudson, 2009). Firstly because of the separate tests used to determine JH, for example the use of the jump and reach test against a wall may impede jumping technique in comparison to FPs (Canavan & Vescovi, 2004; Duncan, Hankey, & Nevill, 2013; Markovic & Jaric, 2005). The validity of the results of these regression studies is not clear (Harman, Rosenstein, Frykman, Rosenstein, et al., 1991; D. L. Johnson & Bahamonde, 1996; Lara et al., 2006; Sayers et al., 1999; Shetty, 2002). For example, no information about the definition of the jump initiation time or method of integration used to determine instantaneous vertical velocity of the whole body centre of gravity (CoG) in a CMJ was provided in any of these studies (Owen, 2008) (Table 2.6.2).

Table 2.6. 2. Vertical jump parameters, variables and definitions needed to measure and estimate power and their inclusion or omission in previous regression studies. Adapted from Owen. (2008)

Variables	Method of integration	Sampling frequency (Hz)	Resolution of A to D converter	Frequency of integration	Definition of time of the start of jump	Definition of jump height (predictor)
Harman et al. (1991) (SJ)	No info	500	12 bit	No info	No info	Yes
Johnson and Bahamonde. (1996) (CMJ)	No info	500	Not info	No info	No info	No
Sayers et al. (1999) (CMJ)	No info	500	Not info	No info	No info	Yes
Shetty. (2002) (CMJ)	No info	100	Not info	No info	No info	No
Canavan and Vescovi. (2003) (CMJ)	No info	500	Not info	No info	No info	No
Lara et al. (2006) (CMJ)	No info	500	Not info	No info	No info	No
Quagiarella et al. (2011) (CMJ)	No info	1000	Not info	No info	No info	Yes
Amonette et al. (2012) (CMJ)	No info	400	Not info	No info	No info	Yes
Duncan et al. (2013) (CMJ)	No info	500	Not info	No info	No info	No
Duncan et al. (2013) (CMJ)	No info	500	Not info	No info	No info	No

Only 3 out of the 10 regression equations were developed for adolescent populations with none-developed for children. Adult regression equations should not be utilised in children as they were developed specifically for adult populations using adult anthropometric data. If adult regression equations are applied this will result in high negative intercept values that are biologically and biomechanically implausible (Duncan, Hankey, & Nevill, 2013). When adult models are used, the lower body mass in children coupled with the higher negative intercept values from adult models will result in a misrepresentation of the actual power values generated in children (Duncan, Hankey, & Nevill, 2013). Very few studies have applied regression equations in children (M. J. D. Taylor et al., 2010) and adolescents (Duncan, Hankey, Lyons, et al., 2013; Duncan, Hankey, & Nevill, 2013). One study has previously attempted to acquire normative data for children; however, important details of the study were not reported, including the jump type that was used, and the method used for documenting JHs (Bovet et al., 2007). More recently, a study by Taylor, Cohen, Voss & Sandercock. (2010) compiling normative power data on children, for the purpose of identification of talented individuals on 1845 children aged 10-15 years old and a study by Ramírez-Vélez et al. (2017) investigating vertical jump and leg power normative data in 7614 Colombian school children aged 9-17.9 years. Both studies estimated power from the Sayers regression equation (Sayers et al., 1999) utilising vertical JH derived from the flight-time method via an instrumented jump mat (NewTest Timing Mat and Takei 5414 Jump-DF Digital Vertical, Probotics Inc, Huntsville, Alabama). While both results would have been useful, a major limitation of this study was the use of the Sayers equation to calculate power. The Sayers equation was specifically developed for use with adults aged 21 years and over and validated on a homogenous sample of males and females. Therefore, it is not appropriate for estimating power in children (Sayers et al., 1999). The reason for utilising this method was that there was no model that had been validated for children (Ramírez-Vélez et al., 2017; M. J. D. Taylor et al., 2010). It has previously been proposed that the use of this prediction equation has resulted in a degree of inaccuracy and should be overlooked (Lara et al., 2006) due to the over-estimation of the equation by 2.7% (M. J. D. Taylor et al., 2010), 8.5% (Duncan, Hankey, & Nevill, 2013) and the underestimation by 8% (Lara et al., 2006). The allowed inclusion of arm swing will significantly impact the results produced as the contribution of arm swing on jump performance enhances momentum and is thought to increase JH by 28% (Lees, Vanrenterghem, & Clercq, 2004). Furthermore, the contact mat (NewTest Jump Mat) used in the study of Taylor and colleagues. (2010), is thought to over-estimate JH by 2.8cm. Therefore, the combination of such imprecision's leads to the proposal that the overall results of the studies contain a considerable level of inaccuracy. For these reasons, Taylor and colleagues. (2010) advised on the use of force-platforms rather than prediction equations for the compilation of more precise data. The second regression equation proposed was developed by Amonette et al. (2012) who investigated peak vertical jump power estimations in 415 youths and young adults. Amonette et al. (2012) highlighted that no significant differences were found between actual and predicted PPO, while other previously published equations produced for PPO estimates were significantly different than actual PPO. Though caution should be used when interpreting individual estimated PPO values due to the large inter participant error (± > 600 W) associated with predictions.

More recently Duncan, Hankey, Lyons, James and Nevill. (2013) compared estimated PPO from FP derived PPO levels in 77 adolescent basketball players, and in another study by Duncan, Hankey and Nevill. (2013) using allometric scaling they identified a model to predict PPO which was suggested as superior to all previously validated PPO regression equations (Duncan, Hankey, Lyons, et al., 2013; Duncan, Hankey, & Nevill, 2013). However, the method of attaining actual PPO via the FP has highlighted a number of issues as the resolution, integration sample frequency, calculation of initiation of start, and CMJ type were not reported. Furthermore, the sample used by Duncan, Hankey, Lyons, James and Nevill. (2013) were elite adolescent athletes and it was not clear whether their allometric model is applicable to the broad range of jump abilities seen in children and other adolescents (Duncan, Hankey, & Nevill, 2013). The need to greatly refine and improve the method to estimate PPO led Duncan, Hankey and Nevill. (2013) to investigate PPO estimation equations in 12 to 16 year old children comparing linear with allometric models in 40 male and 51 female British school children. Duncan, Hankey and Nevill. (2013) firstly compared actual PPO measurements against commonly used regression equations and found significant differences between the actual PPO and estimation PPO. It should be noted again that the force plate utilised by Duncan, Hankey and Nevill. (2013) was sampling at 400 Hz with no mention of resolution, integration sampling frequency and how initiation of the start of the jump was established. In addition, they also presented linear and allometrically scaled regression equations suited for 12 to 16 year old boys and girls demonstrating no significant differences from linear (2443.9 ± 787.9 W, $R^2 = 0.866$) and allometric equations (2459.8 ± 832.8 W, $R^{2\ =}$ 0.888) to estimate PPO when compared to actual PPO (2539.4 ± 868.6 W). A significant advance within the literature has been made from previous regression equations when the use of FPs are not available as the use of allometric scaling enables a greater understanding about the extent of performance differences that are attributable to differences in body size. However, small sample sizes, a sample of 60 for the linear model and 31 for the allometric equation, could be considered a limitation to represent the age range of 12-16 year old boys and girls. Allometric scaling CMJ variables in children has been discussed further in Appendix V: Extension to Review of Literature

2.6.3 Measurement of Power in Children

Few studies have reported the measurement of power in children from a CMJ measured via a force platform (FP). There are also limitations associated with the methodology used to determine power in each study making the results unclear. Table 2.6.3 list all the current studies that report a criterion measure of peak mechanical power in children.

Table 2.6. 3. Methodology of data collection and method specification of studies using force platforms to report mechanical power normative data in children

Author	Sample Frequency (Hz)	Force Range (N)	Jump start Initiation identification	A/D Resolution	Determination of BW	Methods of Integration
Fricke et al. (2005)	NR	7200	NR	NR	NR	NR
Busche et al. (2013)	NR	1200	NR	NR	NR	NR
Sumnik et al. (2013)	800	NR	NR	NR	NR	NR
Gabel et al. (2016)*	800	NR	NR	NR	NR	NR

*Note NR = Not Reported, * = no reliability data*

The four studies highlighted significant age effects occurring for absolute PPO with no significant sex differences occurring until the age of 12 (Busche et al., 2013; Fricke, Weidler, Tutlewski, & Schoenau, 2006; Gabel et al., 2016; Sumnik et al., 2013). This was then followed by a plateau in adolescent girls whereas the boys showed a steady increase throughout childhood. In contrast, both PPO and peak force (Fmax) demonstrated a continuous increase as body mass increased in both sexes. Sumnik et al. (2013) suggested the differences between sexes were due to earlier termination of growth in girls and the different actions of hormones (oestrogen and testosterone) on muscle growth. All four studies provide reference data for jumping mechanography. The term jumping mechanography was used by Fricke et al. (2006), Busche et al. (2013), Sumnik et al. (2013) and Gabel et al. (2016) and it refers to measuring dynamic muscle function in clinical setting using portable ground reaction force plates (Veilleux & Rauch, 2010). The demonstration of language of the authors show an apparent lack of knowledge of the immense body of sports science literature dedicated to jump analysis using a force platform. In addition, the dearth of descriptions of the methodology reported to calculate mechanical power output limits the potential use of this reference data for all four studies. For example, PPO was reported in the four studies as the product of force and velocity, with velocity derived from numerical integration as described by Cavagna. (1975). A crucial aspect of deriving velocity requires a correct integration start time which was not was not reported. Furthermore, a significant limitation to all four studies for providing reference data on PPO is the lack of participant especially children. For example, a participant group of nine cannot represent age and sex reference data for that population group. With regards to the reliability of the measured PPO variable Veilleux and Rauch. (2010) found the CMJ variables PPO and Fmax measured via a mechanography to be reliable for measuring child and adult populations. However, the measured CMJ was utilized with arm swing and not arms akimbo with the limitations of using arms swing during a CMJ previously stated. The use of arm swing which was utilized by Fricke et al. (2006), Busche et al. (2013) and Sumnik et al. (2013) using stating reliability produced by Veilleux and Rauch. (2010). In contrast, Gabel et al. (2016) reported no reliability data. As a result the majority of the studies reported CMJ neuromuscular variables and primarily the variable PPO is unclear due to reliability and a lack of description of the methodology. A substantial evidence has amounted that a suitable criterion method for assessing peak mechanical power output in child populations must be developed.

2.7 Chapter Conclusions

The literature review in this chapter has summarised the current evidence base surrounding the measurement of lower limb neuromuscular performance from a countermovement jump (CMJ).

Though a wide variety of methods can be utilised to assess a CMJ, the criterion method is via force platform (FP). The assessment of CMJ neuromuscular performance via a FP has been shown to identify a wide range of neuromuscular variables expressed in terms of work, velocity displacement, power and times, which have been linked to various factors such playing standard (Baker & Newton, 2008) and sprint performance (Hansen, et al., 2011) in eite adult populations. More recently the measurement of CMJ neuromuscular performance variables in child populations has been found to aid in the identification of a variety of factors such as overweight and obesity (Bovet, Auguste and Burdette, 2007), bone strength (Weeks et al, 2008; Schoenau and Fricke, 2008), maturation (Malina et al, 2004), talent identification (Till et al, 2015; Lloyd et al, 2015;

Lloyd et al, 2013) and coordination (Korff et al 2009; Clark et al, 1989; Jensen et al, 1994).

Though the FP method is by far the most complex method to CMJ neuromuscular performance as several neuromuscular variables such as jump height, power, velocity, impulse and rate of force development are mathematically derived from the force-time history. Subsequently, in order to mathematically derive these variables a number of key factors such as the sampling frequency of the FP, the resolution of the FP , the selection of the vertical force range, the method of measuring bodyweight, the identification of the start of the jump and the method of integration, must be considered and selected as these factors can contribute to random and systematic error being accumulated during a jump (Hatze, 1998; Kibele, 1998; Owen et al., 2014; Street et al., 2001; Vanrenterghem et al., 2001). While the assessment of neuromuscular performance in elite adults has an established criterion method for measuring CMJ instantaneous peak mechanical power output (PPO) and other derived variables (Owen et al., 2014), no such method exist for children, with no studies reporting how all these key factors are defined and considered to reduce random and systematic error in their measurements. For example, one variable of particular interest within the research of children is the measurement of PPO. However, it is also clear from this review that there are significant variations in the equipment used to collect the data, the methods used to calculate the variables and how the various neuromuscular performance variables have been defined. In turn, this has resulted in a number of study's results being unclear. Given this, it is suggested that, prior to utilizing CMJ variables to measure neuromuscular performance, a criterion FP method for children should be developed in order to ensure all CMJ neuromuscular performance variables such as PPO are reliable, valid and age appropriate. Therefore, the overarching aim of this thesis is the determination of methods to assess CMJ neuromuscular performance variables in children.

Chapter 3 General Methods

3.1 Introduction

This chapter describes the general methods used with this thesis. This thesis examines countermovement jump (CMJ) variables measured from a force plate (FP) in children aged 7 to 11 years and in elite adults. Further specific details of individual studies and review of measurement techniques are outlined in the relevant experimental chapters and appendices. However, there was considerable overlap across the individual studies and, as such, this chapter will provide a description of those methods.

3.2 Participants

Participants were recruited from schools, regional and national teams across Wales. The first study utilised elite adults and children aged 7 to 11 years. The following three studies the participants were children aged 7 to 11 years. All participants undertook a standardized warm up relevant to their age and training experience (Appendix V: Additional Methods Table 10.1), which was prescribed by a United Kingdom Strength and Conditioning Association (UKSCA) accredited strength and conditioning coach who has experience with training elite adults and young children (who was part of the research team). Each participant was previously familiar with conducting CMJ, due to jumping being a natural feature of play in children and forming an element of elite adult training and testing regimes.

Ethical approval for experimental chapters 1 to 4 (PG/2014/35) was granted in agreement with the guidelines and polices of the Applied Sport Technology Exercise and Medicine Research Centre (A-STEM) Ethical Committee. All participants were volunteers and gave informed written assent (Appendix I). Permission to recruit participants was obtained from their school district and head teacher, coaches and the participants. Further permission for any participants under the age of 18 years was obtained from the children's parents/guardians via an information sheet and consent letter sent home by their coach or head teacher (Appendix II, Appendix III). All testing for children aged 7 to 11 years took place during their school physical education lesson, which was performed within their facilities under the supervision of a first aid trained individual and their teacher. All participants on the day of testing were asked if they would like to participate, emphasising that there was no requirement to take part, in addition to the coach/teacher explaining the procedures involved with this study. All personnel directly involved with the testing of participants under 18 had undertaken a valid police Criminal Record Bureau (CRB) check with evidence given prior to study (Appendix IV).

3.3 Data Collection

All participants performed a CMJ in *Experimental Chapters 1, 2, 3 and 4*. A CMJ was selected to assess neuromuscular performance as all participants were familiar with a CMJ as it formed a natural feature of play or was part of the participant's strength and conditioning regime. Variables attained from a CMJ were attained from the vertical component of the ground reaction force (VGRF) collected using a portable FP with a built in charge amplifier (Type 92866AA, Kistler Instruments Ltd., Farnborough, United Kingdom). All participants were given standardised instruction to stand on the FP and remain as still as possible for the period of quiet standing and to jump on the command of the tester. Unless specified differently, the analogue signal from the FP was sampled at a frequency of 1,000 Hz chosen as this is the highest sampling frequency used to measure PPO in a CMJ (Bevan, Owen, Cunningham, Kingsley, & Kilduff, 2009; Hatze, 1998; Kibele, 1998; Owen et al., 2014). A sample length of 10 seconds was used for all jumps. A 20 kN vertical force range and 16-bit analogue to digital converter (Kistler Instruments Ltd, Farnborough, United Kingdom) using Kistler's Bioware (version 5.2.3.5), was chosen according to the criterion method established by Owen et al. (2014). The FP was factory calibrated and before testing underwent calibration checks using masses that were traceable to national standards.

3.3.1 Countermovement Jump

Countermovement jump force-time histories were collected for children aged 7 to 11 years and elite adults. The participants were instructed to stand on the FP and after a 5 second period of quiet standing the researcher indicated they were ready to begin sampling (Street et al., 2001). With regards to testing children aged 7 to 11 years old, initial difficulties was highlighted by the research team, the difficulty was when the research team member instructed a child to not step on the force platform straightaway, so that the research team member was able to rest and zero the force platform prior to the collection of a CMJ. A line of tape was placed in front of the force platform, and the child was told to "step on the yellow tape" though trivial this enabled to child wait patiently and allow the research member to ensure the force platform was correctly prepared for data (Figure 3.1). Each participant performed one CMJ, during which they were told to "jump as high as possible". A CMJ involves a countermovement phase where there is a simultaneous flexion of the hips, knees and ankle joints, lowering the body's centre of gravity (CoG). The propulsion phase involves simultaneous extension of the hips, knees, and ankle joints, where sufficient upward speed of the CoG is generated to lift the body off the ground (Bartlett, 1997). Depth was self-selected by the participants and, in order to isolate the lower limbs, participants hands were kept akimbo (Owen et al., 2014).

Figure 3. 1. Example of a change in methodological procedure with use of yellow tape when collecting countermovement jump force-time history data in children aged 7 to 11 years.

3.3.2 Reliability

Previous reliability studies investigating CMJ variables in children reported intraclass correlation coefficients (ICC) and coefficient of variations (CV) for peak force (Fmax) (ICC 0.94, CV 12.7%), rate of force development (RFD) (ICC not reported, CV 25%), jump height (JH) (ICC 0.97, CV 5%) and PPO (ICC 0.98, CV 2.6%) to be reliable variables in children (Focke et al., 2013; Veilleux & Rauch, 2010). It should be noted that the PPO value reported by Veilleux and Rauch. (2010) is with regards to a CMJ with arm swing and not arms akimbo. A pilot reliability study was previously performed for 46 children (21 girls and 25 boys) from school years 3 to 6 (age: 9.17 ± 0.56 years, stature: 1.36 ± 0.09 m, mass: 35.6 ± 10.3 kg), whereby 3 CMJs were performed in the morning and 3 CMJs were performed, with a 5 minute rest between each rep in the morning and afternoon (all CMJs were performed with arm akimbo). A two-way repeated measures analysis of variance (ANOVA) test was completed to identify the existence of any sex x trial interaction for peak power, CVs and ICCs were investigated between trials, for both genders, as means of identifying if the individual trials expressed any association with each other. The results of the pilot study identified that CMJ peak mechanical power output (PPO) is a very reliable neuromuscular performance test in primary school children, as there was no significant difference ($p > 0.05$) between attempt number ($p > 0.05$) or the combination of sex and attempt number ($p > 0.05$). Average CVs ranged from 10-14% for boys and 15-18 % for girls with combined overall CVs ranging from 14-16% across the six trials. Average ICCs ranged from 0.841-0.969 with a mean ICC of 0.923 for boys, and 0.924-0.987 with a mean ICC of 0.923 for girls with a combined range of 0.957-0.986 with a mean value of 0.971 across the 6 trials (Fowler, 2012; Jones, 2012). Previous research has identified that CV below 15% variation and over 0.80 for ICC is deemed reliable for measuring a biological system (Atkinson & Nevill, 1998; Stokes, 1985). This illustrates that jumping vertically is not a novel skill but is well-practiced through play amongst children and makes it a highly repeatable test for power in children aged 7 to 11 years and that one CMJ can collected to represent the neuromuscular performance of a child. Jumping in elite adults has previously been shown to be reliable (Owen et al., 2014).

3.3.3 Determination of Bodyweight, Body Mass and Stature

Bodyweight (BW) was taken to be the mean value of the VGRF during a 1 second period of quiet standing of the CMJ assessment whilst the participant remained stationary. Body mass (BM) was determined by dividing BW by acceleration due to terrestrial gravity (taken as g = 9.81 $m.s^{-2}$) (Thompson & Taylor, 2008). Stature was determined to the nearest 0.1cm using a stadiometer (Harpenden Portable Stadiometer, Holtain Ltd., Pembrokeshire, United Kingdom). To ensure standardisation in the measurement of anthropometric variables the standard procedures outlined by

Lohmann, Roche & Martorell. (1988) were followed. To measure stature, participants were asked to stand barefoot with their heels touching the back of the stadiometer. The participant was asked to look straight ahead with arms relaxed by their sides. The researcher then gently held the child's head in two hands so that light upwards pressure was applied under the jaw anteriorly and occiput (base of the skull) posteriorly to provide maximum extension of the spine. Care was taken not to tilt the head and to maintain the Frankfort position of the head, whereby the inferior aspect of the orbit was parallel with upper margin of the ear canal (Lohmann et al., 1988). The participant was asked to breathe in and then out and to relax their shoulders without lifting their heels from the ground. The horizontal head plate was then lowered until it made contact with the highest point of the participant's head and stature was recorded to the nearest 0.1 cm.

3.3.4 Identification of Start, End of Jump and Sampling Frequency

Due to variations in the methods used across the experimental chapters the identification of start and end of jump and sampling frequency will be discussed in described in Chapter 6 and Chapter 7.

3.3.5 Principles of Deriving Countermovement Jump Force-Time History Variables

Due to the variations in the methods used across the experimental study the methods will be described in each chapter. Therefore, only the principles of attaining CMJ output variables such as numerical integration and differentiation will be discussed in additional methods (Appendix V).

3.4 Statistical Analysis

All data for each of the four studies was found to be normally distributed confirmed using Z-scores for skew and kurtosis. Homogeneity of variance was assessed by Levene's test for equality of variances (Levene, 1960) before statistical tests were selected. Due to variations in the statistical methods used across each experimental study, further details are given within each respective chapters. Statistical analysis was performed using SPSS software (Version 22; IBM SPSS Inc., Chicago, IL), with significance set at $p \leq 0.05$. Effect sizes were determined using partial eta squared (η_p^2). Large magnitudes of effects were taken as η_p^2 = 0.14, medium-sized effects were η_p^2 = 0.06 and small effects were η_p^2 = 0.01 as proposed by Cohen. (1973). Data are presented as mean ± standard deviation.

Thesis Map

Chapter 4: Experimental Study 1: The Effect of Age and Sex on Countermovement Jump Kinetics between Children Aged 7 to 11 Years and Elite Adults	
Objective	To investigate the effect of age and sex on absolute unprocessed countermovement jump (CMJ) variables between children aged 7 to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children
Key Findings	
Chapter 5: Experimental Study 2: The Effect of Body Size on Countermovement Jump Kinetics in Children Aged 7 to 11 Years	
Objective	
Key Findings	
Chapter 6: Experimental Study 3: Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump for Children Aged 7 to 11 Years	
Objective	
Key Findings	
Chapter 7: Experimental Study 4: The Development of Regression Equations to Estimate Peak Mechanical Power Output in Children Aged 7 to 11 Years	
Objective	
Key Findings	

Chapter 4 Experimental Study 1: The Effect of Age and Sex on Countermovement Jump Kinetics in Children Aged 7 to 11 Years and Elite Adults

4.1 Introduction

The literature review has demonstrated that the use of countermovement jump (CMJ) variables to be of great benefit to child populations with regards to monitoring a variety of aspects such as maturation, talent identification and assessing children for motor difficulties (Clark et al., 1989; Jensen et al., 1994; Korff et al., 2009; Lloyd & Oliver, 2013; Malina et al., 2005). For example, the assessment of CMJ neuromuscular performance has been applied as a potential screening tool for examining muscle function in children at risk of musculoskeletal impairment (Clark et al., 1989; Jensen et al., 1994; Korff et al., 2009; Schoenau & Fricke, 2008; Weeks et al., 2008). However, the methods used to determine CMJ neuromuscular performance variables in children, such as peak mechanical power output (PPO), impulse, jump height (JH) and rate of force development (RFD), have been employed without first establishing the reliability, validity, and criterion method including technical specifications, making it inapplicable for use in such populations. There is only one current criterion method established within the literature for measuring a number of CMJ variables which was developed for elite adult's populations enabling an accurate and valid method of deriving important force-time history variables (Owen et al., 2014). However, it is not known whether the elite adult criterion method (EACM) is suitable for other populations such as children aged 7- 11 years, or whether a new criterion method is needed to be developed. This subsequently identified the first research question:

What differences are there between children aged 7 to 11 years and elite adults in absolute CMJ variables?

Limited information is currently available comparing children and adults in CMJ performance measured via a FP as discussed within the literature review. Although significant differences may be anticipated, it remains to be reported which parameters differ and the magnitude of difference. Why an elite adult population was chosen to compare against untrained children is because the EACM was developed for elite adults and thus must be compared to children. Though the differences may be due to age, sex or training status, it is not the purpose of this study to identify the mechanism but to identify whether significant absolute difference occurs. This would then inform whether a new criterion method needed or the EACM could be applied to child populations. Many of the CMJ neuromuscular variables that would be useful to differentiate elite adults and children cannot be used as they require a criterion method and a number of mathematical processes such as numerical integration to calculate them. This subsequently developed the second *Experimental Chapter 1* research question:

What countermovement jump variables can be measured across age, sex and population?

From a seemingly simple question of identifying differences between children and elite adults, has subsequently led to a novel way of describing and defining CMJ which has not be considered before within the literature. However, it took numerous attempts to identify, define and describe clearly what CMJ variables could be used and why. The initial stages of this research question highlighted the two strands of CMJ variables as primary and secondary which was defined through a number of practical examples. However, for the purpose of clarity a definition was needed and developed, with an evolution of describing these two types of CMJ variables as non-derived/raw and derived variables. However, due it their close comparison to derived and non-derived SI units and ambiguity of the definition of key variables such as mechanical power within the field of biomechanics and strength and conditioning (Winter et al, 2016), the definitions were changed so that no confusion would occur. Therefore, this thesis has described CMJ variables as being processed and unprocessed (A list of unprocessed and processed CMJ variables and there definitions are presented in Table 10.2 Appendix VI Extension to *Experimental Chapter 1*). A processed CMJ variable is a variable that requires a start time (t_s) prior to its calculation, for example, PPO, JH, RFD and impulse. Whereas, an unprocessed CMJ variable is a variable that does not require a t_s and can be attained through inspection of the force-time (F/T) history curve, for example peak force (Fmax), bodyweight (BW) and basic rate of force development (BRFD).

The importance quantifying CMJ variables in this way allows the identification of what variables can be used across age, sex and population. For example, a processed variable requires a t_s prior to its calculation, therefore processed variables cannot be used as t_s is part of the EACM and, as such, might be invalid for child populations (Hatze, 1998; Kibele, 1998; Owen et al., 2014; Vanrenterghem et al., 2001). Indeed, any variable that requires integration of the F/T history of a CMJ such as PPO, velocity, and displacement will first need a t_s and therefore cannot currently be used to characterize differences between different populations groups, because if the wrong time point for t_s is identified erroneous variations in processed CMJ variables will occur. However, CMJ F/T variables that do not require a t_s prior to their calculation such as unprocessed CMJ variables can be currently measured and utilised across population, age groups and sexes. Therefore, the objective of *Experimental Chapter 1* was to investigate the effect of age and sex on absolute unprocessed CMJ variables in children aged to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children.

The null hypotheses of *Experimental Chapter 1* was that there would not be significant differences between elite adult and children aged 7 to 11 years.

4.2 Methodology

4.2.1 Participants

Participants were comprised of two groups: 40 primary school children aged 7 to 11 years and 40 elite adults (professional male rugby players and international female netballers), with each group including an equal number of male and female participants. Anthropometric measures for the participants are presented in table 5.1. Each participant performed one CMJ. Five participants were randomly selected from school years 3, 4, 5 and 6 using a random number generator in EXCEL (Microsoft, 2013) to represent the 20 boys and 20 girls aged 7 to 11 years.

.

4.2.2 Measurements

The VGRF-time histories for each participant's CMJ were recorded and unprocessed CMJ variables of the corresponding force trace were determined, by inspection, for each participant.

The variable BW has previously been described in Chapter 3 General Methods. The Fmax of the jump was taken to be the one sample with the highest numerical value of the VGRF during the sampling period of the F/T history. The in-jump minimum value of VGRF was taken as the sample with the lowest numerical value prior to Fmax force during the sampling period of the F/T history. This will be referred as in-jump minimum force (IMF). The in-jump force range value of VGRF was taken as the difference between the IMF and Fmax. This will be referred to as in jump vertical force range (IFR). In addition, the time between IMF and Fmax was also collected. This will be referred as in-jump vertical force range time (IFRt). Basic rate of force development (BRFD) of the VGRF was taken as IFR divided by IFRt.

$$BRFD = \frac{IFR}{IFRt}$$

Equation 4

Whereby BRFD = basic rate of force development ($N.s^{-1}$), IFR = in-jump vertical force range (N), FRt = in-jump vertical force range time (s).

4.2.3 Statistical Analysis

Data was confirmed to be normally distributed and variance was homogenous, so a two-way analysis of variance (ANOVA) was used to determine the influence of age and sex, and their interaction on absolute unprocessed CMJ F/T history variables. Simple main effects (SME) were subsequently used to identify the location of significant differences due to sex and age. Data are presented as mean ± standard deviation.

4.3 Results

Participant anthropometric characteristics are presented in Table 4.1.

Table 4. 1. Anthropometric measures by group and sex

Group and Sex	Age (years)	Stature (m)	Body mass (kg)
Girls (n = 20)	9.6 ± 1.1	1.42 ± 0.20	35.0 ± 11.0
Boys (n = 20)	9.4 ± 1.3	1.42 ± 0.17	33.1 ± 6.9
Elite Female (n = 20)	23.2 ± 2.6	1.75 ± 0.07	72.3 ± 8.4
Elite Male (n = 20)	23.0 ± 4.4	1.86 ± 0.06	100.3 ± 14.1

Mean ± standard deviation

4.3.1 Age and Sex

Significant differences of age and sex effects on BW were found ($p < 0.0001$, η_p^2 = 0.867; $p < 0.0001$, η_p^2 = 0.287; respectively), with a significant interaction between this variables ($p < 0.0001$, η_p^2 = 0.348). Specifically, while BW was found to increase with age, SME revealed significant sex differences for BW between elite adult males and females ($p < 0.0001$) but no significant differences between boys and girls (p = 0.559).

In accord with BW, the variables Fmax, IMF and IFR were also found to be significantly influenced by age and sex ($p < 0.0001$, η_p^2 = 0.183 – 0.834, $p < 0.05$, η_p^2 = 0.018 – 0.379: respectively), with a significant interaction effect between age and sex on each variable ($p < 0.05$, η_p^2 = 0.02 – 0.379, Table 4.2; Figure 4.1). Specifically, while Fmax, IMF and IFR were found to increase with age, SME revealed significant sex differences for between elite adult males and females ($p < 0.05$) but no significant differences between boys and girls ($p > 0.05$). In contrast, while a significant age effect was found in BRFD with a higher BRFD in adults compared to children irrespective of sex ($p < 0.0001$, η_p^2 = 0.368), there was no interaction between these variables (p = 0.240, η_p^2 = 0.018, p = 0.215, η_p^2 = 0.020: respectively).

Table 4. 2. Effects of age and sex on bodyweight, in-jump minimum vertical force, peak vertical force, in-jump vertical force range and basic rate of force development

	Bodyweight (N)	In Jump Minimum Vertical Force (N)	Peak Vertical Force (N)	In Jump Vertical Force Range (N)	Basic Rate of Force Development ($N.s^{-1}$)
Girls	343 ± 108	146 ± 65	885 ± 254	744 ± 238	3151 ± 1342
Boys	342 ± 67	149 ± 65	885 ± 206	742 ± 171	3123 ± 1259
Elite Adult Female	710 ± 82	190 ± 93	1674 ± 239	1483 ± 235	5431 ± 1995
Elite Adult Male	984 ± 138	292 ± 158	2520 ± 370	2226 ± 440	6460 ± 2629
Age: P (η_p^2)	$p < 0.0001$ (0.867)	$p < 0.0001$ (0.179)	$p < 0.0001$ (0.834)	$p < 0.0001$ (0.795)	$p < 0.0001$ (0.368)
Sex: P (η_p^2)	$p < 0.0001$ (0.287)	$p = 0.026$ (0.064)	$p < 0.0001$ (0.379)	$p < 0.0001$ (0.301)	$p = 0.240$ (0.018)
Age * Sex: P (η_p^2)	$p < 0.0001$ (0.348)	$p = 0.036$ (0.057)	$p < 0.0001$ (0.379)	$p < 0.0001$ (0.303)	$p = 0.215$ (0.02)

Mean ± standard deviation

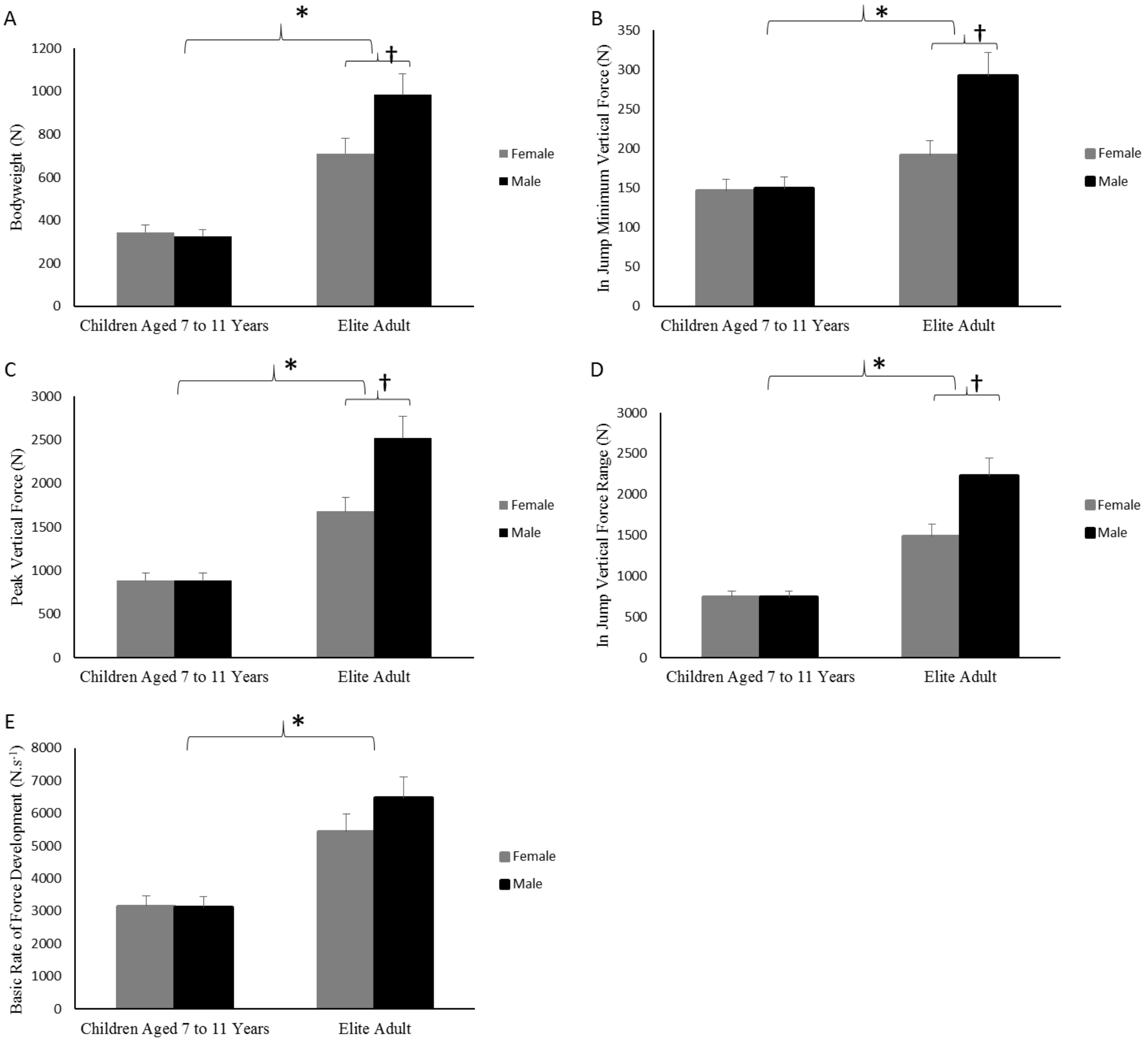

Figure 4. 1. Effects of age and sex on group absolute countermovement jump variables

Where A = bodyweight, B = in-jump minimum vertical force, C = peak vertical force, D = in-jump vertical force range, and E = basic rate of force development, asterisk (*) indicates significant difference between age groups ($p < 0.05$) and dagger (†) indicates significant differences between sex ($p < 0.05$)

4.4 Discussion

The purpose of this study was to examine the effect of age and sex on unprocessed countermovement jump variables obtained from the analysis of a VRGF-time history of a CMJ in order to establish if there were significant differences between absolute values in children aged 7 to 11 years and elite adults. The results of this study demonstrate there was a significant influence of age on all unprocessed CMJ kinetic variables between elite adults and children aged 7 to 11 years. Therefore, the null hypotheses could be rejected. In addition, the influence of sex was dependent on age with no significant sex differences between the boys and girls compared to significantly higher values in elite adult males and elite adult females.

4.4.1 Age

Though it was not the purpose of this study to identify the mechanisms for the observed age related changes for the variables BW, IMF, Fmax, IFR and BRFD, the potential mechanism for these differences observed between adults and children may be associated with body size from the effect of maturation which results in rapid increases in muscle cross-sectional area, alterations in fascicle length and muscle volume and changes in pennation angle, all of which are associated with greater force output (Lloyd et al., 2014). The results of this study are in general agreement with other studies that investigated the effects of age on absolute CMJ variables (Focke et al., 2013; Gabel et al., 2016; Raffalt et al., 2016a, 2016b; Sumnik et al., 2013; M. J. D. Taylor et al., 2010). For example, previous research by Focke et al. (2013), Sumnik et al. (2013) and Taylor et al. (2010), demonstrated that variables such as Fmax, JH, PPO and estimated PPO increased with age. However, the identified variables were only measured in children in these studies with further inter-study comparisons limited by the methodological techniques used to attain unprocessed and processed F/T history CMJ variables. For example, Taylor et al. (2010) investigated the vertical jumping and leg power in 1845 school children aged 10-15 years and demonstrated significant age effects on JH and estimated PPO, showing similar trends in the unprocessed CMJ variables as in this study. However, the use of an instrumented jump mat, and arm swing to attain JH and an adult regression equation to attain PPO confounds further interpretation of their data. Such discrepancies are likely to contribute to the poor reliability previously reported, such as the 12.7% coefficient of variation (CV) reported for Fmax, 13.1% CV for relative Fmax and 5% CV for JH in 13 children aged 7 to 11 years (Veilleux & Rauch, 2010) or the 20-25% CV for RFD (Focke et al., 2013). If this was used for the talent identification or for a health assessment, such as coordination the child could be placed in the incorrect group or given an inappropriate intervention.

All six studies that reported the assessed CMJ performance via a FP in adolescents and children measured the variable Fmax. However, only Sumnik et al. (2013) reported Fmax as an absolute value while three studies reported Fmax normalised to BW

(Busche et al., 2013; Focke et al., 2013; Gabel et al., 2016) and two studies reported Fmax allometrically scaled to two-thirds body mass (Raffalt et al., 2016b, 2016a), all producing contrasting findings in their results. For example, Focke et al. (2013) found no significant age differences between Fmax and RFD, with RFD decreasing with age. These findings were supported by Busche et al. (2013) and Gabel et al. (2016) who found no significant age differences with normalised Fmax and PPO. In contrast, Raffalt et al. (2016b) found significant age differences in allometrically scaled Fmax with children and adults with children significantly higher values. This study found significant increases in the variables absolute Fmax and BRFD as age increased, which is in agreement with the findings of Sumnik et al. (2013) who found absolute Fmax increased with age. As certain aspects of the EACM are population specifics the findings of this study suggests that a new criterion method must be developed for children aged 7 to 11 years, as this study demonstrated that all unprocessed CMJ variables for children aged 7 to 11 years were significantly lower when compared to elite adults. Furthermore, due to the differences observed with the literature on CMJ performance in children the effect of body size should be investigated due to its impact on affecting the significance of the results presented within the literature which may conclude more than one criterion method must be developed for children aged 7 to 11 years.

4.4.2 Sex

The findings of this study is in agreement with previous research (Sumnik et al., 2013; Temfemo et al., 2009). For example, the study by Temfemo et al. (2009) who investigated the relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls, found that there was no significant sex difference in vertical jump performance variables such as JH between boys and girls up to the age of 11 years. Though different variables and methodologies to attain these variables were used such as JH instead of BW, Fmax and IMF the results both follow the same trend. In contrast, the studies that investigated normalised CMJ F/T history variables such as normalised Fmax and RFD found significant sex differences occurring between boys and girls from aged 4 to 17 years (Focke et al., 2013), with girls demonstrating significantly higher values at all age ranges. The study by Temfemo et al. (2009) and Sumnik et al. (2013) also highlighted that significant sex differences occurred between boys and girls from the ages of 13 and 14 year of age and upwards respectively. Which are in agreement with the findings of this study as significant sex differences were observed between elite adults male and female unprocessed variables BW ($p < 0.0001$), IMF ($p = 0.017$) Fmax ($p < 0.0001$) and IFR ($p < 0.0001$). The potential mechanisms for the significant sex differences occurring may be as a result of the effects of maturation. Greater increases in leg length and morphological changes are observed in male adolescent as a result of greater anabolic hormonal concentrations (Beunen & Malina, 2008; Borms, 1986; Meylan, Cronin, Oliver, Hughes, & Manson, 2014; Neu, Rauch, Rittweger, Manz, & Schoenau, 2002; O'brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2010; Parker, Round, Sacco, & Jones, 1990; Temfemo et al., 2009). The potential greater effects of maturation on males could be attributed to the significant sex differences observed within this study between elite male adult and elite female adults. As elite male adults demonstrated higher stature values (1.75 ± 0.07 m versus 1.84 ± 0.06 m) and significantly higher BW values (710 ± 82 N versus 984 ± 138 N).

Surprisingly, no significant interaction effects between age and sex was found for the variable BRFD. In addition, SME revealed no significant sex differences in the elite adult between males and female. This finding is in contrast to the rest of the findings and therefore could be suggested that the changes in BRFD observed with increased age ($p < 0.0001$) as highlighted in this study are independent of hormonal and morphological changes resulting in no significant sex differences observed between the elite male group and elite female group.

4.5 Conclusion

This study has achieved the first objective of this thesis which was to investigate the effect of age and sex on absolute unprocessed CMJ variables in children aged to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children. Specifically, this study answered two research questions by highlighting a number of unprocessed CMJ variables that can be used across age, sex, population. The use of unprocessed CMJ variables: BW, IMF and Fmax highlighted that they are sensitive to the influences of age and showed significant sex differences after the onset of puberty. Future research should consider the effect of body size in children due to the confounding difference currently presented with the literature. The need to develop a new criterion method is indicated for determining processed CMJ variables as the EACM is population specific, and significant difference were observed between an elite adult population and children aged 7 to 11 years.

Thesis Map

Chapter 4: Experimental Study 1: The Effect of Age and Sex on Countermovement Jump Kinetics between Children Aged 7 to 11 Years and Elite Adults	
Objective	To investigate the effect of age and sex on absolute unprocessed countermovement jump (CMJ) variables between children aged 7 to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children
Key Findings	Significant age differences occurred between elite adults and children aged 7 to 11 years, with elite adults having significantly higher CMJ kinetic values ($p \leq 0.05$). No significant sex differences were observed in the child group ($p > 0.05$), whereas significant sex differences were observed between elite adults with males having significantly larger values ($p \leq 0.05$)
Chapter 5: Experimental Study 2: The Effect of Body Size on Countermovement Jump Kinetics in Children Aged 7 to 11 Years	
Objective	To investigate the importance of accounting for body size in their interpretation of countermovement jump kinetics in children aged 7 to 11 years
Key Findings	
Chapter 6: Experimental Study 3: Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump for Children Aged 7 to 11 Years	
Objective	
Key Findings	
Chapter 7: Experimental Study 4: The Development of Regression Equations to Estimate Peak Mechanical Power Output in Children Aged 7 to 11 Years	
Objective	
Key Findings	

Chapter 5 Experimental Study 2: The Effect of Body Size on Countermovement Jump Kinetics in Children Aged 7 to 11 Years

5.1 Introduction

Experimental Chapter 1 identified a number of variables (bodyweight (BW), peak force (Fmax), in-jump minimum force (IMF), in-jump force range (IRF) and basic rate of force development (BRFD)), which can be measured across different ages and between sexes as these variables can be identified regardless of, age, sex, specific specification or further processing of the countermovement jump (CMJ) force-time (F/T) history. *Experimental Chapter 1* took children aged 7 to 11 years as a homogenous group to determine if there were significant differences to elite adults, in order to identify whether a new criterion method should be developed for determining CMJ neuromuscular performance variables performed on a force platform (FP). Having determined that there were significant differences between elite adult and children, further analysis is needed prior to the development of a new criterion method in order to identify whether there are any sex and age differences within child group itself. This subsequently led to the development of the research question:

Is more than one criterion method needed for measuring countermovement jump variables in children aged 7 to 11 years?

The differences in FP CMJ neuromuscular performance variables BW, Fmax, IMF, IFR and BRFC for children aged 7 to 11 years have not yet been fully characterised, in addition to the variety of ways in which they can be presented. Many neuromuscular performance variables, such as muscular strength demonstrate a strong positive relationship with body size (Jaric, 2002). Consequently, an individual with a larger body size will often express higher absolute neuromuscular performance values. This must be considered when producing normative reference data or investigating findings in intervention studies in children. For example, did Fmax increase as a result of the a strength and conditioning programme implemented by the researcher over a 10 week period or did Fmax only increase as a result of an increase in body size. If body size was not accounted for potentially the findings of the study could be interpreted wrong. This led to the development of the research question:

What impact does body size have on interpreting countermovement jump kinetics in children aged 7 to 11 years?

Statistical techniques may be used in order to remove the influence of body size on neuromuscular performance variables. This can be achieve by normalising to body weight or allometrically scaling the CMJ neuromuscular variables. As highlighted within the literature review limited research exists for the measurement of allometrically scaled CMJ neuromuscular performance variables measured via a FP and requires further investigation. Whereas, the use of absolute and normalised variables has been used interchangeably with CMJ neuromuscular performance in child research, this may lead to confusion and clarity of the findings when comparing to other research. For example, a study by Focke et al. (2013) investigated the effects of age, sex and activity level on CMJ performance in children and adolescents. The results showed that absolute jump height (JH) increases significantly with age, whereas when JH was normalised to body height, the influence of age was ameliorated. If JH was reported only as an absolute or normalised value the findings in result would be limited and potentially unclear for comparison. Therefore, the objective of *Experiential Chapter 2* was to investigate the importance of accounting for body size in the interpretation of countermovement jump kinetics in children aged 7 to 11 years. This would be achieved by comparing absolute, normalised and allometrically scaled unprocessed CMJ variables in children aged 7 to 11 years and would answer the research question: whether more than one criterion method needed for measuring countermovement jump variables in children aged 7 to 11 years?

The null hypotheses of *Experimental Chapter 2* was that there would not be significant absolute differences and significant differences in CMJ variables when accounting for body size in children aged 7 to 11 years.

5.2 Methodology

5.2.1 Participants

Force-time histories were collected for 160 primary school children aged 7 to 11 years. The participants were comprised of four groups, with each group consisting of 20 boys and 20 girls. Anthropometric measures for the participants are presented in table 5.1. Each participant performed one CMJ. Participants (n = 160) were randomly selected from school years 3, 4, 5 and 6 using a random number generator in EXCEL (Microsoft, 2013) to represent the 20 boys and 20 girls for each school year.

5.2.2 Measurements

The F/T histories for each participant's CMJ were recorded and unprocessed CMJ variables of the F/T history as described in Experimental Chapter 1 was determined for each participant.

In order to control for the effects of BW on the neuromuscular variables. Each unprocessed CMJ variable was divided by BW. Units were then represented as BW's.

$$Normalised\ variable = \frac{unprocessed\ variable}{BW}$$

Equation 5

Whereby BW= body weight (N).

In order to control for the effects of body mass an allometric modelling approach was used based on the recommendations of Nevill & Holder. (1995). This was determined by Pearson product moment correlation coefficients to determine the degree of relationship between body mass and unprocessed CMJ variables. Logarithmic transformation was performed on each variable and body mass in boys and girls. A linear regression analysis was then applied to the logarithmic transformed data to determine the regression coefficients (Table 5.2). Allometric scaled variables were then obtained by

$$Allometric\ Scaled\ Variable = \frac{unprocessed\ variable}{BM^b}$$

Equation 6

Where BM = body mass (kg) and b = coefficient attained from regression analysis from BM and the investigated variable.

5.2.3 Statistical Analysis

Data was confirmed to be normally distributed and variance was homogenous, a two-way analysis of variance (ANOVA) was used to determine the influence of age, sex and their interaction on absolute, normalised and allometrically scaled unprocessed CMJ F/T history variables. Bonferroni corrected post hoc t-tests and simple main effects (SME) were subsequently used to identify the location of significant differences due to sex and age. Data are presented as mean ± standard deviation.

5.3 Results

Participant anthropometric data are presented in Table 5.1, and logarithmic regression coefficients for allometrically scaling unprocessed F/T history CMJ variables are presented in Table 5.2.

Table 5. 1. Anthropometric data by group and sex for age, stature and body mass

	Age (years)		Stature (m)		Body Mass (kg)	
Group	Girls (N = 20)	Boys (N = 20)	Girls (N = 20)	Boys (N = 20)	Girls (N = 20)	Boys (N = 20)
Year 3	8.0 ± 0.6	8.1 ± 0.7	1.29 ± 0.13	1.37 ± 0.16	27.1 ± 6.1	28.1 ± 7.9
Year 4	9.4 ± 0.5	9.2 ± 0.7	1.39 ± 0.19	1.49 ± 0.19	30.3 ± 6.2	33.2 ± 5.8
Year 5	10.2 ± 0.7	10.0 ± 0.7	1.39 ± 0.14	1.37 ± 0.06	36.2 ± 8.1	41.2 ± 10.4
Year 6	10.9 ± 0.8	10.8 ± 0.7	1.46 ± 0.11	1.43 ± 0.11	43.6 ± 10.6	37.8 ± 8.4

Mean ± standard deviation

Table 5. 2. Logarithmic regression coefficients for allometric scaling of body mass to unprocessed force-time history CMJ variables: minimum vertical force, peak vertical force, vertical force range and basic rate of force development

Logarithmic Regression Coefficient				
	In Jump Minimum Force	Peak Force	In Jump Vertical Force Range	Basic Rate of Force Development
b	1.540	0.752	0.652	0.256
t	9.511	17.892	11.31	1.785
p	<0.0001	<0.0001	0.756	0.076

5.3.1 Absolute Countermovement Jump Variables

Significant age effects were found for BW, IMF, Fmax and IFR ($p < 0.0001$, η_p^2 = 0.121 - 0.409; respectively) with post hoc t-test revealing the differences occurred between years groups 3 and 4 against year groups 5 and 6 ($p < 0.05$). No significant age effect was observed for BRFD ($p < 0.217$, $\eta_p^2 = 0.029$; respectively). No significant sex differences were observed between boys and girls ($p > 0.05$, $\eta_p^2 = 0.0001 - 0.015$; respectively) and no interaction effect was observed for any of the absolute CMJ variables ($p > 0.05$, $\eta_p^2 = 0.002 - 0.004$; respectively) (Table 5.3; Figure 5.1). SME revealed no significant sex differences ($p > 0.05$) between boys and girls for any year group.

Table 5. 3. Effects of age and sex on absolute CMJ variables, bodyweight, in- jump minimum vertical force, peak vertical force, in-jump vertical force range and basic rate of force development

	Bodyweight (N)		In-Jump Minimum Vertical Force (N)		Peak Vertical Force (N)		In-Jump Vertical Force Range (N)		Basic Rate of Force Development ($N.s^{-1}$)	
Group	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys
Year 3	266 ± 59	276 ± 77	91 ± 38	119 ± 79	733 ± 133	722 ± 150	641 ± 141	606 ± 134	3243 ± 1115	2926 ± 1643
Year 4	297 ± 61	325 ± 56	141 ± 160	152 ± 80	823 ± 177	885 ± 161	714 ± 171	740 ± 168	3638 ± 1797	3438 ± 2357
Year 5	384 ± 69	403 ± 10	162 ± 61	194 ± 68	1031 ± 230	1046 ± 202	868 ± 216	851 ± 173	3954 ± 2030	3265 ± 1343
Year 6	427 ± 103	445 ± 97	182 ± 95	202 ± 106	1098 ± 274	1140 ± 233	920 ± 248	924 ± 188	3991 ± 1743	3948 ± 2548
Age: P (η_p^2)	p < 0.0001 (0.409)		p < 0.0001 (0.121)		p < 0.0001 (0.381)		p < 0.0001 (0.295)		p = 0.217 (0.029)	
Sex: P (η_p^2)	p = 0.137 (0.015)		p = 0.126 (0.015)		p = 0.396 (0.005)		p = 0.851 (0.000)		p = 0.295 (0.007)	
Age * Sex: P (η_p^2)	p = 0.966 (0.002)		p = 0.961 (0.002)		p = 0.860 (0.005)		p = 0.990 (0.004)		p = 0.886 (0.004)	

Mean ± standard deviation

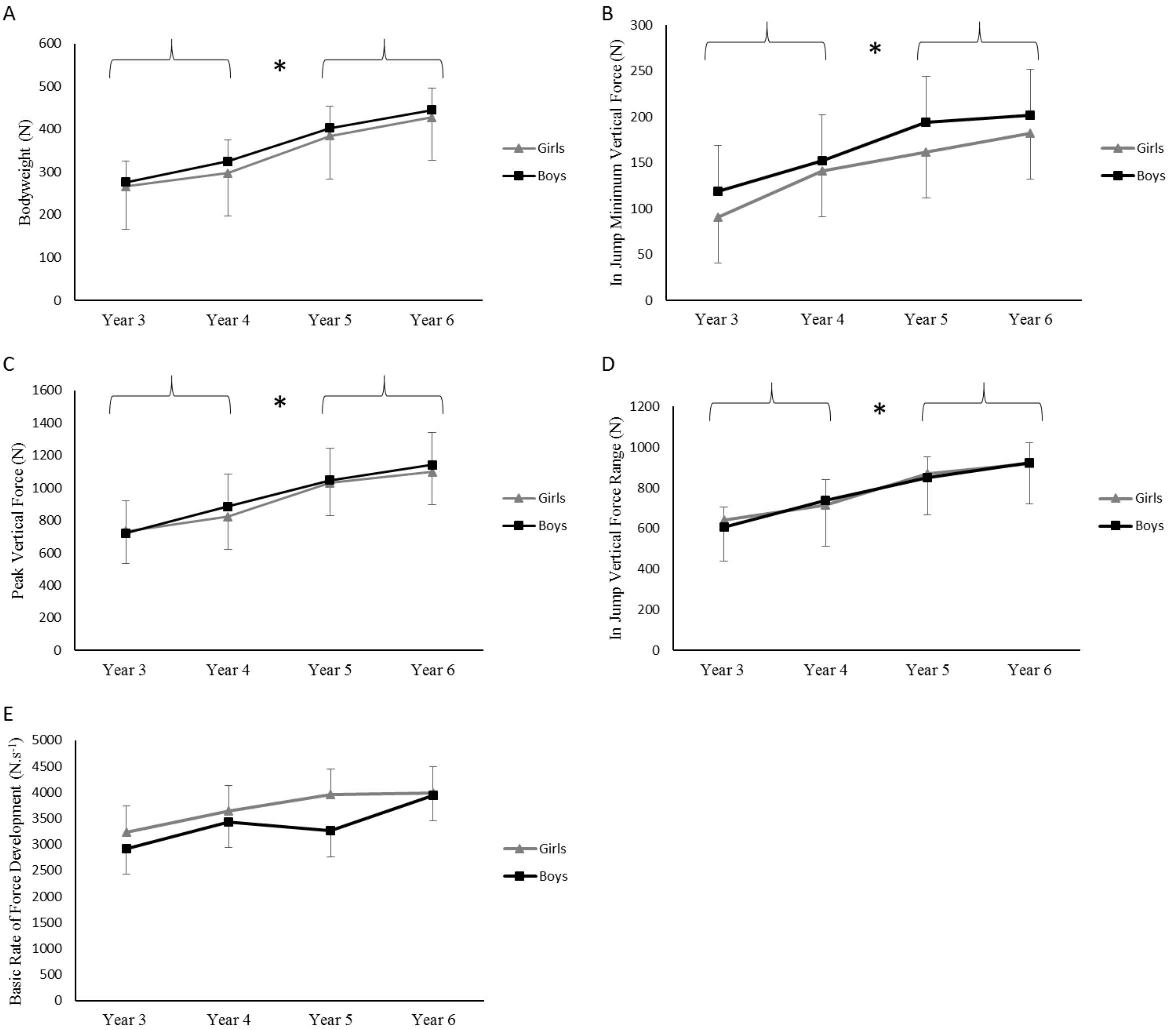

Figure 5. 1. Effects of age and sex on absolute countermovement jump variables by year group

Where A = bodyweight, B = in-jump minimum vertical force, C = peak vertical force, D = in-jump vertical force range, E = and basic rate of force development, asterisk (*) indicates significant difference between school year groups 3 and 4 to school years 5 and 6 (p < 0.05)

5.3.2 Normalised Countermovement Jump Variables

No significant age differences occurred between any year group ($p > 0.05$, $\eta_p^2 = 0.017 - 0.052$; respectively). No significant sex differences were observed between boys and girls ($p > 0.05$, $\eta_p^2 = 0.0002 - 0.011$; respectively) and no interaction effect was observed for any of the normalised CMJ variables ($p > 0.05$, $\eta_p^2 = 0.003 - 0.004$; respectively) (Table 5.4; Figure 5.2). SME revealed no significant sex differences ($p > 0.05$) between boys and girls for any year group.

Table 5. 4. Effects of age and sex on normalised CMJ variables, in jump minimum vertical force, peak vertical force, in jump vertical force range and basic rate of force development

	Normalised-In Jump Minimum Vertical Force (BW)		Normalised Peak Vertical Force (BW)		Normalised In-Jump Vertical Force Range (BW)		Normalised Basic Rate of Force Development ($BW.s^{-1}$)	
Group	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys
Year 3	0.35 ± 0.14	0.40 ± 0.19	2.80 ± 0.34	2.69 ± 0.50	2.44 ± 0.38	2.29 ± 0.61	12.44 ± 3.91	11.45 ± 7.31
Year 4	0.47 ± 0.56	0.45 ± 0.20	2.80 ± 0.51	2.75 ± 0.50	2.45 ± 0.58	2.31 ± 0.62	12.75 ± 6.64	11.14 ± 8.58
Year 5	0.42 ± 0.13	0.47 ± 0.10	2.68 ± 0.32	2.65 ± 0.44	2.25 ± 0.35	2.17 ± 0.48	10.08 ± 4.14	8.62 ± 4.53
Year 6	0.42 ± 0.18	0.43 ± 0.15	2.57 ± 0.25	2.60 ± 0.41	2.15 ± 0.34	2.13 ± 0.44	9.26 ± 3.38	9.20 ± 5.95
Age: P (η_p^2)	p = 0.457 (0.017)		p = 0.189 (0.031)		p = 0.077 (0.044)		p = 0.053 (0.052)	
Sex: P (η_p^2)	p = 0.536 (0.003)		p = 0.550 (0.002)		p = 0.205 (0.011)		p = 0.265 (0.008)	
Age * Sex: P (η_p^2)	p = 0.904 (0.004)		p = 0.900 (0.004)		p = 0.939 (0.003)		p = 0.933 (0.003)	

Mean ± standard deviation

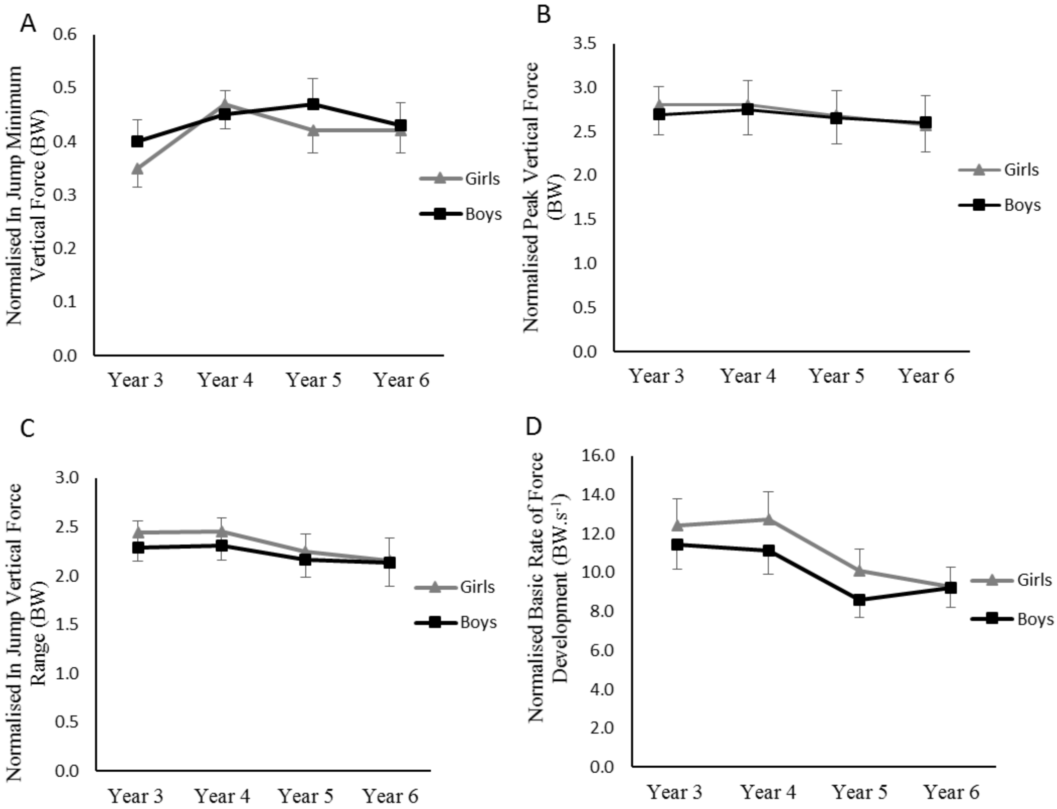

Figure 5. 2. Effects of age and sex on normalized countermovement jump variables by year group

Where A = normalised in-jump minimum vertical force, B = normalised peak vertical force, C = normalised in-jump vertical force range, and D = normalised basic rate of force development. No significant differences were found

5.3.3 Allometrically Scaled Countermovement Jump Variables

Results for logarithmic regression coefficient's for body mass to unprocessed CMJ variables are represented in Table 5.2. No significant age differences occurred between any year group ($p > 0.05$, η_p^2 = 0.005 - 0.042; respectively). No significant sex differences were observed between boys and girls ($p > 0.05$, η_p^2 = 0.0001 - 0.008; respectively) or an interaction effect was observed for any of the allometrically scaled CMJ variables ($p > 0.05$, η_p^2 = 0.003 - 0.005; respectively) (Table 5.5; Figure 5.3). SME revealed no significant sex differences ($p > 0.05$) between boys and girls for any year group.

Table 5. 5. Effects of age and sex on allometrically scaled CMJ variables, in jump minimum vertical force, peak vertical force, in jump vertical force range and basic rate of force development

	Allometric In-Jump Minimum Force (N.BM^{b-1})		Allometric Peak Force (N. BM^{b-1})		Allometric In-Jump Vertical Force Range (N. BM^{b-1})		Allometric Basic Rate of Force Development (N.s^{-1}. BM^{b-1})	
Group	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys
Year 3	11.32 ± 4.45	13.58 ± 7.12	55.85 ± 5.62	53.89 ± 8.72	68.61 ± 9.88	64.41 ± 14.7	990.51 ± 308.05	900.00 ± 523.84
Year 4	15.98 ± 18.73	16.08 ± 7.61	57.39 ± 9.82	57.43 ± 9.66	71.16 ± 15.74	69.34 ± 16.86	1077.48 ± 534.91	990.91 ± 706.95
Year 5	15.69 ± 5.14	18.02 ± 4.33	58.16 ± 7.48	57.74 ± 8.19	71.69 ± 12.30	69.26 ± 12.88	1044.50 ± 491.18	871.06 ± 384.99
Year 6	16.42 ± 7.33	17.28 ± 7.28	56.98 ± 6.29	58.05 ± 7.98	70.58 ± 12.24	70.16 ± 12.19	1016.63 ± 405.40	1006.64 ± 629.53
Age: P (η_p^2)	p = 0.086 (0.042)		p = 0.314 (0.023)		p = 0.488 (0.016)		p = 0.843 (0.005)	
Sex: P (η_p^2)	p = 0.325 (0.006)		p = 0.804 (0.000)		p = 0.301 (0.007)		p = 0.268 (0.008)	
Age * Sex: P (η_p^2)	p = 0.929 (0.003)		p = 0.867 (0.005)		p = 0.939 (0.003)		p = 0.917 (0.003)	

Mean ± standard deviation

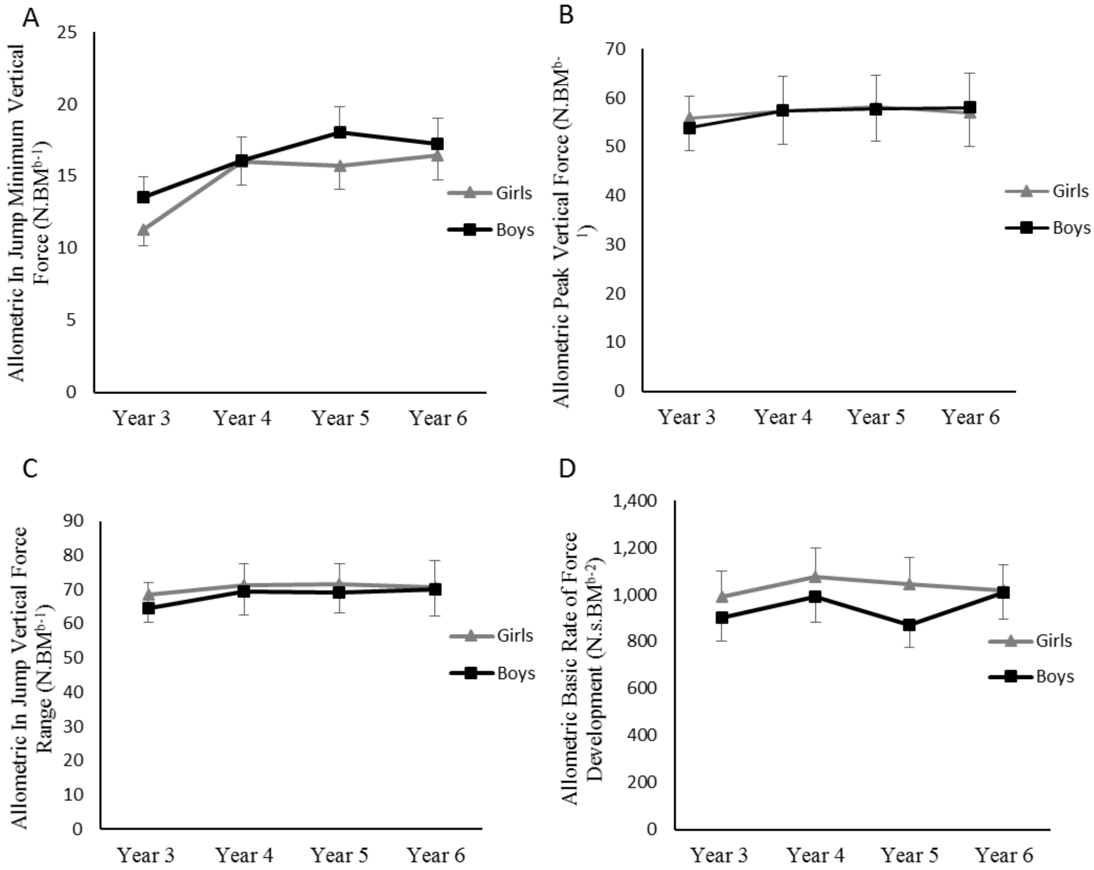

Figure 5. 3. Effects of age and sex on allometrically scaled countermovement jump variables by year group

Where A = allometric in-jump minimum vertical force, B = allometric peak vertical force, C = allometric in-jump vertical force range, and D = allometric basic rate of force development. No significant differences were found

5.4 Discussion

The purpose of this study was to investigate the importance of accounting for body size in the interpretation of countermovement jump kinetics in children aged 7 to 11 years. Achieved by comparing absolute, normalised and allometrically scaled unprocessed CMJ variables in children aged 7 to 11 years. The findings of this study demonstrated that sex does not influence CMJ performance in pre pubertal children. The variables BW, IMF, Fmax and IFR were found to increase with age, although BRFD was not influenced. Normalising and allometric scaling to account for changes in body size ameliorated these apparent age-related effects, suggesting changes are not a function of age per se. Therefore, the null hypotheses could be rejected.

5.4.1 Absolute Countermovement Jump Variables

In agreement with previous studies (Sumnik et al., 2013; Temfemo et al., 2009), no significant sex differences were observed for any absolute CMJ variables BW, MIF, Fmax, IFR and BRFD. CMJ sex differences appear to manifest from the ages of 12 in boys and girls, thought to occur as a result of the onset of puberty (Focke et al., 2013; Tanner, 1962; Temfemo et al., 2009), with boys developing greater leg lengths and muscle volumes than girls resulting in better neuromuscular performance scores (Bitar, Vernet, Coudert, & Vermorel, 2000; Seger & Thorstensson, 2000; Temfemo et al., 2009). In contrast, Focke et al. (2013) observed significant age and sex effects in CMJ JH and normalised JH for all year groups in 1835 children and adolescents aged 4-17 years. It was not stated why significant sex differences occurred in children below the age of 11 years, though Focke et al, (2013) reported a high percentage of variability for the results of jump height in participants below 9 years of age (10-20%) stating that this CMJ performance variable should not be used for individuals.

The age related effects observed in the present study may be attributable to the concomitant processes of growth and maturation; given that BRFD was not influenced by age this may suggest that this parameter is not sensitive to changes in body size and may be indicative that this is an appropriate parameter for use across the age and maturity spectrum. The findings of this study are in agreement with Sumnik et al. (2013) who sought to develop reference data for jumping mechanography in 796 healthy children and adolescents aged 6-18 years, reporting that both peak mechanical power output (PPO) and Fmax values linearly increased with age in both sexes pre-puberty, with no significant difference between sexes. Significant differences were subsequently observed in adolescents with boys having significantly higher CMJ values (Sumnik et al., 2013). It should be noted, however, that fundamental details regarding the method of calculating PPO and specifications utilised to measure CMJ variables were missing from this study, thereby limiting inter-study comparison and the potential utility of this reference data. The current findings demonstrate similar patterns to those observed in other measured neuromuscular variables in children. For example, previous research has demonstrated that sprint speed significantly increases every 2-3 years (Bassa, Kotzamanidis, Patikas, & Paraschos, 2001; Cherif et al., 2012). The potential mechanisms for this increase in sprint development is thought to occur from significant strength increases every second year due to increases with body size (Bassa et al., 2001; Cherif et al., 2012).

5.4.2 Normalised Countermovement Jump Variables

Age and sex had no effect on unprocessed CMJ variables normalised peak force (NFmax), normalised in-jump minimum force (NIMF), normalised in-jump force range (NIFR) and normalised basic rate of force development (NBRFD). The findings of this study were in accord with previous research which identified no significant age differences between NFmax and normalised RFD and no other studies have investigated NIMF and NIFR CMJ values. If significant differences had occurred across year groups for NFmax, in addition to the absolute findings of Fmax this would have identified the changes would have occurred independent of body size. The potential mechanisms would therefore be considered to be neuro-developmental changes in performance which is a common belief in pre-pubertal strength and conditioning research (Lloyd & Oliver, 2013). This study shows that changes in absolute performance in primary school children are predominantly a result of increases in body size and therefore contradicts this common belief. Though NFmax remained constant previous research has found normalised RFD to actually decrease with age (Focke et al., 2013), this was also highlighted with the findings of this study though the decrease in NBRFD with age was not significant. The findings of this study (no sex differences between any primary school year group) is further supported by Busche et al. (2013) who investigated mechanography in childhood and Gabel et al. (2016) who investigated reference data for jumping mechanography in 715 Canadian children, adolescent and young adults. The results of both studies highlighted significant sex and age differences but were not observed until the age of 11 years, after which boys demonstrated higher values of normalised PPO to body mass and normalised Fmax to bodyweight. However, as previously stated the validity of the three studies highlighting normalised CMJ F/T variables may be questioned, which further highlights a need for a valid criterion method for determining processed CMJ variables in children.

5.4.3 Allometrically Scaled Countermovement Jump Variables

Age and sex had no effect on unprocessed CMJ variables allometrically scaled peak force (AFmax), allometrically scaled in-jump minimum force (AIMF), allometrically scaled in-jump force range (AIFR) and allometrically scaled basic rate of force development (ABRFD). Allometric scaling seeks to enable inter-group comparisons independent of the potential confounding influence of differences in body size. In the present study, when allometrically scaled, the previously observed age-related differences were ameliorated. There is a lack of research considering the influences of body size in the interpretation of age and sex related differences in CMJ performance. Although some previous studies have examined the allometric scaling of CMJ performance in children, it has been for the purpose of predicting performance by other means (Duncan, Hankey, Lyons, et al., 2013; Fricke, Stabrey, Tutlewski, & Schoenau, 2009) or by investigating intra-subject variability (Raffalt et al., 2016b). Specifically, Raffalt, Alkjaer & Simonsen. (2016b) demonstrated that allometrically scaled knee joint power and Fmax was greater in children when compared to adults but the results were only reported graphically. Duncan, Hankey, Lyons, James & Nevill. (2013) investigated peak power prediction in junior basketballers, comparing linear and allometric models to predict PPO and highlighting that allometric regression models were more appropriate than traditional linear models. Fricke et al. (2009) examined allometrically scaled CMJ Fmax and its relationship to maximal isometric grip strength (MIGF) in German primary school children, demonstrating that MIGF was a good predictor of CMJ Fmax. No sex comparisons were presented.

The results of this study demonstrate that, firstly, boys and girls can be grouped together as there are no significant differences between any absolute, normalised or allometrically scaled CMJ variables. If body size is accounted for children aged 7 to 11 years can also be represented as one homogenous group. Secondly, the effect of body size significantly effects the representation of results and, therefore, any future studies must consider and report both absolute and scaled variables in order to enable appropriate comparisons across studies. This is vital for research investigating changes in performance which should be considered independently of the natural increases in performance engendered by increases in body size with age.

Given these findings, future research should develop 2 criterion methods for children aged 7 to 11 years. Furthermore, future studies may wish to consider the most informative representation of data; a potential limitation of this study was the use of school year groups to classify children for comparisons. Indeed, whilst parametric assumptions of normality and homogeneity of variances were maintained for each group in this present study by taking randomised samples from a larger pool of data, the current method of assessing children by year group may not be representative as testing took place at only one time point in the year. This may result in a skewed distribution as the youngest and oldest possible ages are not measured in the year group. Previous research has suggested a 3 month intervals for the frequency of assessment for longitudinal tracking of maturation status as it enables worthwhile changes in growth to take place, however whether this is suitable to monitor CMJ variables remains to be elucidated (Lloyd et al., 2014; Stratton & Oliver, 2013).

5.5 Conclusion

This study has achieved the second objective of this thesis which was to investigate the importance of accounting for body size in the interpretation of countermovement jump kinetics in children aged 7 to 11 years. This was achieved by comparing absolute, normalised and allometrically scaled unprocessed CMJ variables in children aged 7 to 11 years. Specifically, this study answered two research questions, highlighting a number of significant findings for the application and representation of children aged 7 to 11 years. Significant age difference were observed for CMJ absolute variables BW, Fmax, IMF and IFR between years 3 and 4 against years 5 and 6 highlighting more than one criterion method should be developed for children aged 7 to 11 years. Furthermore, normalised and allometrically scaled CMJ data highlighted no significant differences for age, sex and interaction between these factors, meaning body size significantly affects the representation of results of children and future studies must consider and report both absolute and scaled values.

Thesis Map

<table>
<tr><td colspan="2">Chapter 4: Experimental Study 1: The Effect of Age and Sex on Countermovement Jump Kinetics between Children Aged 7 to 11 Years and Elite Adults</td></tr>
<tr><td>Objective</td><td>To investigate the effect of age and sex on absolute unprocessed countermovement jump (CMJ) variables between children aged 7 to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children</td></tr>
<tr><td>Key Findings</td><td>Significant age differences occurred between elite adults and children aged 7 to 11 years, with elite adults having significantly higher CMJ kinetic values ($p \leq 0.05$). No significant sex differences were observed in the child group ($p > 0.05$), whereas significant sex differences were observed between elite adults with males having significantly larger values ($p \leq 0.05$)</td></tr>
<tr><td colspan="2">Chapter 5: Experimental Study 2: The Effect of Body Size on Countermovement Jump Kinetics in Children Aged 7 to 11 Years</td></tr>
<tr><td>Objective</td><td>To investigate the importance of accounting for body size in their interpretation of countermovement jump kinetics in children aged 7 to 11 years</td></tr>
<tr><td>Key Findings</td><td>Significant age differences occurred for absolute CMJ variables for school years 3 and 4 to years 5 and 6 ($p > 0.05$). No significant age or sex differences were observed for normalised or allometrically scaled values ($p > 0.05$). No significant sex differences were observed for any absolute CMJ variables ($p > 0.05$)</td></tr>
<tr><td colspan="2">Chapter 6: Experimental Study 3: Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump for Children Aged 7 to 11 Years</td></tr>
<tr><td>Objective</td><td>To establish a criterion protocol for the measurement of lower body instantaneous peak mechanical power output (PPO) and other CMJ variables using the force platform criterion method for children aged 7 to 11 years</td></tr>
<tr><td>Key Findings</td><td></td></tr>
<tr><td colspan="2">Chapter 7: Experimental Study 4: The Development of Regression Equations to Estimate Peak Mechanical Power Output in Children Aged 7 to 11 Years</td></tr>
<tr><td>Objective</td><td></td></tr>
<tr><td>Key Findings</td><td></td></tr>
</table>

Chapter 6 Experimental Study 3: Development of a Criterion Method to Determine Lower Body Peak Mechanical Power Output from a Countermovement Jump in Children Aged 7 to 11 Years

6.1 Introduction

The results reported in *Experimental Chapter 1* indicate that it is reasonable to assume that the elite adult criterion method (EACM) developed by Owen et al. (2014) is not suitable for children aged 7 to 11 years, as all countermovement jump (CMJ) performance variables were significantly lower in children aged 7 to 11 years when compared to elite adults. Consequently, elements of the specifications of the EACM will need to re-evaluate and could potentially be reduced, as the equipment price is cheaper when the specification is lower due to lower manufacturing costs. The results in *Experimental Chapter 2* identified that significant absolute differences occurred between school year groups 3 & 4 and 5 & 6. This identified that two criterion methods are required for children aged 7 to 11 years. *Experimental Chapter 3* moves towards determining processed CMJ variables primarily focusing on attaining an accurate measure of lower body peak mechanical power output (PPO) in children. The ability to be able to derive an accurate measure of PPO in children is of vast importance, as previously stated the variable PPO is associated with talent identification, maturation, bone health and coordination (Clark et al., 1989; Jensen et al., 1994; Korff et al., 2009; Lloyd & Oliver, 2013; Malina et al., 2005; Schoenau & Fricke, 2008; Weeks et al., 2008). As significant differences were observed between elite adults and children this may mean less stringent specification are required and this cheaper equipment can be manufactured increasing the accessibility to measure PPO and other processed variables in children. For example, of implemented with school to provide a mass screening for children with motor difficulties such as developmental coordination disorder (DCD), this could help reduce the over referral rate currently seen in the national health service and provide earlier interventions to children that have DCD. Therefore, the objective of *Experimental Chapter 3* was to establish a criterion protocol for the measurement of PPO produced during a CMJ using the FP method. The criterion protocol was established using the key variables of vertical force range and resolution, force sampling frequency and resultant force integration frequency, method of integration, determination of bodyweight (BW) and the determination of the initiation of the jump. These key variables formed the research questions of this study and will be addressed within this chapter.

The null hypotheses of *Experimental Chapter 3* is that the specifications for children aged 7 to 11 years will not be less stringent that the elite adult criterion method.

6.2 Methodology

6.2.1 Participants

Force time-histories were collected for 40 children aged 7 to 11 years. Participants comprised of two groups: Group 1 20 children from UK school years 3 and 4 and group 2 20 children from UK school year 5 and 6, with each group consisting of an equal number of boys and girls. The two groups were selected as the findings of *Experimental Chapter 2* demonstrated significant differences between these school year groups ($p < 0.05$). Anthropometric measures for the participants are presented in Table 6.1Participant anthropometric data are presented in Table 6.1.

Table 6. 1. Anthropometric data by group for age, stature and body mass

Group	Age (years)	Stature (m)	Body Mass (kg)
Group 1	8.41 ± 0.81	1.42 ± 0.16	30.01 ± 6.84
Group 2	10.62 ± 0.58	1.45 ± 0.15	37.68 ± 7.85

Mean ± standard deviation

6.2.2 Measurements

The force-time (F/T) histories were used to determine BW, the influence of vertical force range and resolution, identification of jump initiation, sampling frequency and the method of numerical integration on PPO of each participant’s whole body centre of gravity (CoG) by systematically varying each variable and monitoring the effect on PPO.

6.2.4.1 Calculation of Power

The determination of instantaneous power was based on the impulse-momentum principle First, the instantaneous velocity was determined from the unfiltered F/T history using the impulse momentum principle. The net vertical component of the ground reaction force (VGRF) was numerically integrated at the sample frequency of the F/T history and divided by body mass to determine instantaneous velocity for time points that correspond with the original F/T history. Instantaneous power was determined as the product of instantaneous velocity and the VGRF (Equation 14) at corresponding time points.

In order to establish a clear, universally applicable criterion protocol for the measurement of PPO, it is necessary to define the following variables: determination of BW, selection of the vertical force range and resolution, identification of the initiation of the CMJ, selection of the sampling frequency and method of numerical integration.

6.2.4.2 Analysis of Body Weight and Body Mass

Bodyweight was taken to be the mean value of the VGRF during a period 1 second of quiet standing of the CMJ test whilst the participant remained stationary prior to the signal to jump. BW was also determined for each resampled F/T history trace (500, 250, 100, 50 and 10 Hz). Body mass (BM) was determined by dividing BW by acceleration due to terrestrial gravity (taken as g = 9.81 $m.s^{-2}$) (Thompson & Taylor, 2008).

6.2.4.3 Selection of the Vertical Force Range

Consequently, it was necessary to consider the force transmitted through each corner transducer as well as the combined, gross vertical force (Figure 6.1) (Owen et al., 2014). The vertical F/T histories for each participants CMJ were recorded and the maximum unfiltered values of the gross force and the corresponding corner transducers components of the gross force were determined by inspection for each participant. This was attained from the highest sampling frequency (1000 Hz). The VGRF range selected for this study was defined as the mean maximum vertical force plus 3 standard deviations (SD) as proposed by Owen et al. (2014). The maximum mean vertical force plus 3 SD was chosen in order to reduce the probability of a corner transducer being exceeded as 97.7% of all values (p = 0.003) would lie within this range. When compared to previous suggestions for selection of the VGRF range of 3 to 3.5 times BW (Kibele, 1998) this does not consider each corner transducer being exceed which would have occurred in 65% and 50% of the jumps for Group 1 and Group 2 respectively when examining the data in a pilot study. This would have caused an erroneous force reading which would not be obvious from the resultant vertical force record.

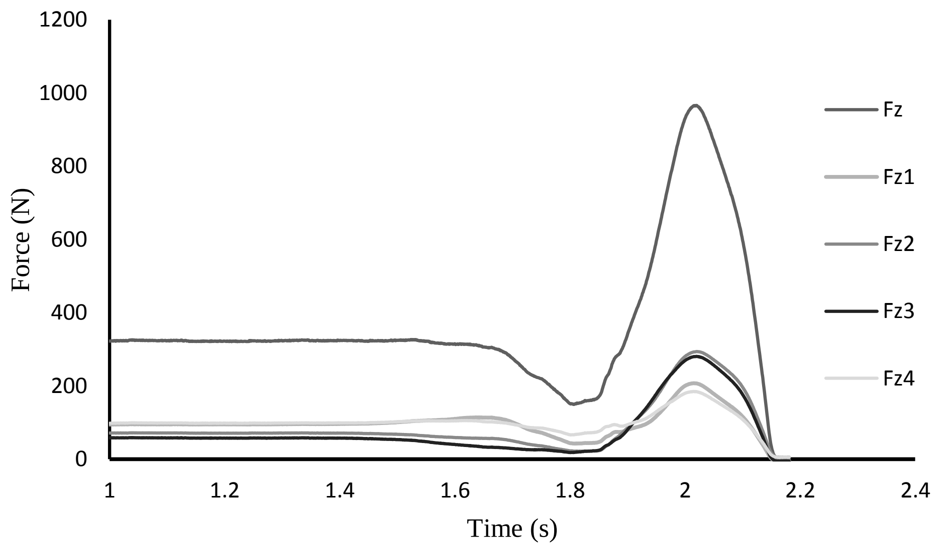

Figure 6. 1. Vertical force-time history of a countermovement jump showing the 4 corner vertical force components. Where Fz = resultant vertical force; Fz1-Fz4, corner vertical components.

6.2.3.4 Identification of the Initiation of a Countermovement Jump

During the stance phase of a CMJ, the VGRF will vary continuously because of slight movement of the participant and noise in the instrumentation, both internal and external. Therefore, it was necessary to define a threshold value of the VGRF during the stance phase, beyond which the jump was defined as having been initiated. If the threshold was set too low or too high an erroneous initiation time would be identified (a miss-trigger). The identification of this instant is important as it also serves as the starting point for integration and as such the condition of vertical velocity of the CoG must equal zero (Owen et al., 2014). The initiation time t_s was defined as the instant after the signal to jump has been given that the VGRF exceeded the mean plus or minus 5SD of the BW as measured in the stance phase. This threshold would reduce the probability of a miss-trigger in the stance phase to $p < 0.0000006$ (i.e. 1 miss-trigger in every 1,744 jumps on average for a stance phase of 1 second sampled at 1000 Hz). However, there is a similarly high probability that t_s as described above, while identifying an instant that has very low probability of being part of the stance phase, will be in the jump phase of the CMJ. Therefore, to investigate the effect of varying t_s and consequently its suitability as a start point, methods similar to those described by Owen et al. (2014) was used. Where, t_s was identified for the 40 CMJ unfiltered F/T histories. The PPO was determined using an integration starting point equal to t_s - 100ms for each participant. The point t_s - 100ms was chosen because it was clearly in the stationary phase of the jump. Values of PPO were then determined using integration starting points of t_s - 90ms through to t_s + 40 ms at intervals of 10 ms for each participant. Consequently, any within participant variation in PPO could be attributed to the integration starting point.

6.2.4.5 Use of Different Sampling Frequencies

To investigate the effect of sampling frequency on the determination of PPO from performance in a CMJ, the F/T histories were then resampled using Bioware's resampling function at 500, 250, 100, 50 and 10 Hz. The PPO was determined for each jump at the 3 unfiltered sampling frequencies using Simpson's rule at the corresponding frequency to determine the velocity-time data. BW was defined as mean VGRF during 1 second of stance. The integration start time, (t_i) was defined as the point when the VGRF, after a signal to jump had been given, exceeded BW plus or minus 5SD. The instant t_i was not optimized; however it served as an initial reference start time. Consequently, the same method (incorporating the determination of BW, integration start time, and Simpson's rule) was used to determine PPO for all jumps, differences in peak power for each jump could be attribute to the different sampling frequencies.

6.2.4.6 Method of Numerical Integration

To investigate the effect of the method of integration on PPO from a CMJ, the 40 unfiltered F/T histories sampled at 1000 and 500 Hz were used. The start point for the integration was taken as t_s (defined above) and each F/T history was integrated twice, first using Simpson's rule and then using the Trapezoidal rule, at the sampling frequency to determine the velocity-time data and hence mechanical vertical power output. The PPO for all jumps were determined by inspection for both methods of integration. Both the Simpson's rule and the Trapezoidal rule are defined and presented in Appendix IV, Additional Methods.

6.2.3 Statistical Analysis

Data was confirmed to be normally distributed and variance was homogenous. 6.2.3.1 Analysis of Bodyweight

Means and standard deviations were determined for values of BW at sampling frequencies of 1000 Hz, 500 Hz, 250 Hz, 100 Hz, 50 Hz and 10 Hz.

6.2.3.2 Analysis of the Vertical Force Range and Resolution

Means and standard deviations were determined for the vertical F/T histories' maximum values of the gross force and the corner transducers' components of the gross force. The vertical force range selection was then determined by the mean Fzc maximum value plus 3 standard deviations as this would result in the corner transducer not being overload in in 99.9% of cases as suggested by Owen et al. (2014). This value was then multiplied by 4 then divided by the group average BW value to produce a value represented in terms of BW as typically reported within the literature (Kibele, 1998; Owen et al., 2014). The resolution accuracy was theoretically suggested based on the force range minimum, group average and maximum vertical force range value which was divided the "number-bit ADC is capable of representing in discrete steps. For example, a 12-bit ADC is capable of representing an analogue signal as 2^{12} that is 4096 discrete steps thus theoretically representing an analogue signal with a range of 0-4 kN in discrete steps of 0.97 N.

6.2.3.3 Analysis of Identification of the Initiation of Countermovement Jump

The PPO determined with an integration start point of t_s - 100 ms was taken as a PPO reference value (PRV). For each participant, difference values were determined for PPO by subtracting each PPO determined using integration starting points of t_s - 90 ms through to t_s + 40ms from the PRV. The values were then normalised to give percentage difference (NPD). For each time point, t_s - 90 ms through to t_s + 40 ms, group mean value and SD were determined for the NPDs. The mean ± 3SD was taken to represent the difference value of PPO, plus the associated uncertainty for any integration start point after t_s - 100ms ($p = 0.003$) as compared with PRV. To investigate the rate of change in the uncertainty of the difference value of PPO, the first derivative of the SD of time series NPD (dSD/dt) was numerically determined (using the central difference method) dividing the rate of change on uncertainty would increase rapidly. Hence, it is reasonable to expect the first derivative of the time series of SD of NPD to identify when the jump had started. It was necessary to analyse the SD of the NPD because the mean value NPD has the potential to show very little change at the beginning of a CMJ as approximately half of the participants executing a CMJ start by first moving up prior to a dipping a countermovement and half of the participant start a CMJ by immediately dipping. Thus at the start of a CMJ, it is likely that an increase in positive lower body power would be mirrored by a corresponding increase in negative lower body power in participants, however, dSD/dt is not sign dependent and hence will identify a positive or negative change in NPD.

6.2.3.4 Analysis of the use of Different Sampling Frequencies

To investigate the difference in LBPP for different sampling frequencies, limits of agreement and mean systematic bias of PPO produced by the 500 Hz, 250 Hz, 100 Hz, 50 Hz and 10 Hz sampling frequencies, in relation to the power outputs of the 1000 Hz sampling frequency were assessed using Bland and Altman plots (Bland & Altman, 1986) after assumptions were met and intraclass correlation coefficients (ICC's) where ICC > 0.80 was considered as minimum acceptability (Baumgartner & Chung, 2001).

6.2.3.5 Method of Numerical Integration

Limits of agreement and mean bias of PPO produced by the 2 methods of numerical integration were assessed using Bland and Altman plots (Bland & Altman, 1986). It was unclear which of the 2 methods of integration produced the more accurate result of PPO. The Trapezoidal rule will exactly measure the area of the Trapezoids produced by discrete sampling, whereas the Simpson's rule may produce a curve that better fits the analogue VGRF time-history. Therefore, the difference values were determined by subtracting the Trapezoidal rule values and the Simpson's rule values from the mean value of the Trapezoidal rule and Simpson's rule values.

6.3 Results

6.3.1 Analysis of Bodyweight

There was no difference in BW for the 6 different sample frequencies (to 1.dp. ± 1 digit) for Group 1 or Group 2 (Table 6.2).

Table 6. 2. Mean and standard deviation of body weights determined at different sampling frequencies during 1 second of quiet standing

	Body Weight (N)					
	1000 Hz	500 Hz	250 Hz	100 Hz	50 Hz	10 Hz
Group 1	294.4 ± 67.1	294.5 ± 67.1	294.5 ± 67.1	294.4 ± 67.1	294.4 ± 67.1	294.2 ± 66.9
Group 2	369.7 ± 77.0	369.7 ± 77.0	369.6 ± 77.0	369.0 ± 76.9	369.6 ± 76.9	369.5 ± 76.8

Mean ± standard deviation

6.3.2 Analysis of the Vertical Force Range and Resolution

The maximum and minimum total vertical force (Group 1: 570.2 - 1140.1 N, Group 2: 649.9-1390.3 N), and mean and standard deviation (Group 1: 792.3 ± 173.2 N, Group 2: 943.2 ± 194.6 N), and the maximum and minimum vertical component forces (Group 1: 51.6 - 450.6 N, Group 2: 6.1 - 436.3 N) and mean and standard deviation (Group 1: 198.1 ± 84.0, Group 2: 235.8 ± 89.5) of the CMJs are represented in Table 6.3 for Group 1 and Group 2. Group 1 had a force range selection of 6.7 X BW and Group 2 had a force range selection of 5.8 x bodyweight.

Table 6. 3. Vertical ground reaction forces produced during a countermovement jump

	Group 1 Fz max (N)	Group 1 Fzc max (N)	Group 1 Body Weight (N)	Group 2 Fz max (N)	Group 2 Fzc max (N)	Group 2 Body Weight (N)
Minimum	570.2	51.6	190.9	649.9	6.1	252.8
Maximum	1140.1	450.6	447.8	1390.3	436.3	575.3
Mean	792.3	279.4	294.4	943.2	313.9	369.7
SD	173.2	71.2	67.1	194.6	74.6	77.0

Fz max = maximum vertical component of the ground reaction force; Fzc max = maximum of the 4 corner component vertical forces.

The accuracies of 6 to 16 bit ADC resolutions are presented in Table 6.4 based on force range selection 6.7 x BW for Group 1 and 5.8 x BW for Group 2, the ADC resolution accuracies was determined from the minimum, group average and maximum force range values (1278, 1927, 2999 N) for Group 1 and (1466, 2144, 3336 N) for Group 2.

Table 6. 4. Influence of force range on theoretical ADC resolution accuracy in discrete steps

	Group 1			Group 2		
	Accuracy of resolution in discrete steps for:					
Number of Bits ADC (Discrete steps)	Minimum Value (N)	Group Average Value (N)	Maximum Value (N)	Minimum Value (N)	Group Average Value (N)	Maximum Value (N)
6-bit (64)	20	30.8	46.9	22.9	33.5	52.2
8-bit (256)	5	7.7	11.7	5.7	8.4	13
10-bit (1024)	1.3	1.9	2.9	1.4	2.1	3.3
12-bit (4096)	0.3	0.5	0.7	0.4	0.5	0.8
16-bit (65536)	0.02	0.03	0.05	0.02	0.03	0.1

6.3.3 Identification of the Initiation of a Countermovement Jump

Figure 6.2 shows individual percentage difference of PPO from NPD for Group 1 and Group 2 while Figure 6.3 shows the rate of change of NPD for Group 1 and Group 2. Figure 6.3 highlights a negative gradient between t_s - 90 to t_s - 50 for both groups at which point between t_s - 40 and t_s - 30 an inflection point occurs for Group 1 and between t_s -50 and t_s - 40 and inflection point for Group 2 where after the gradient increases rapidly.

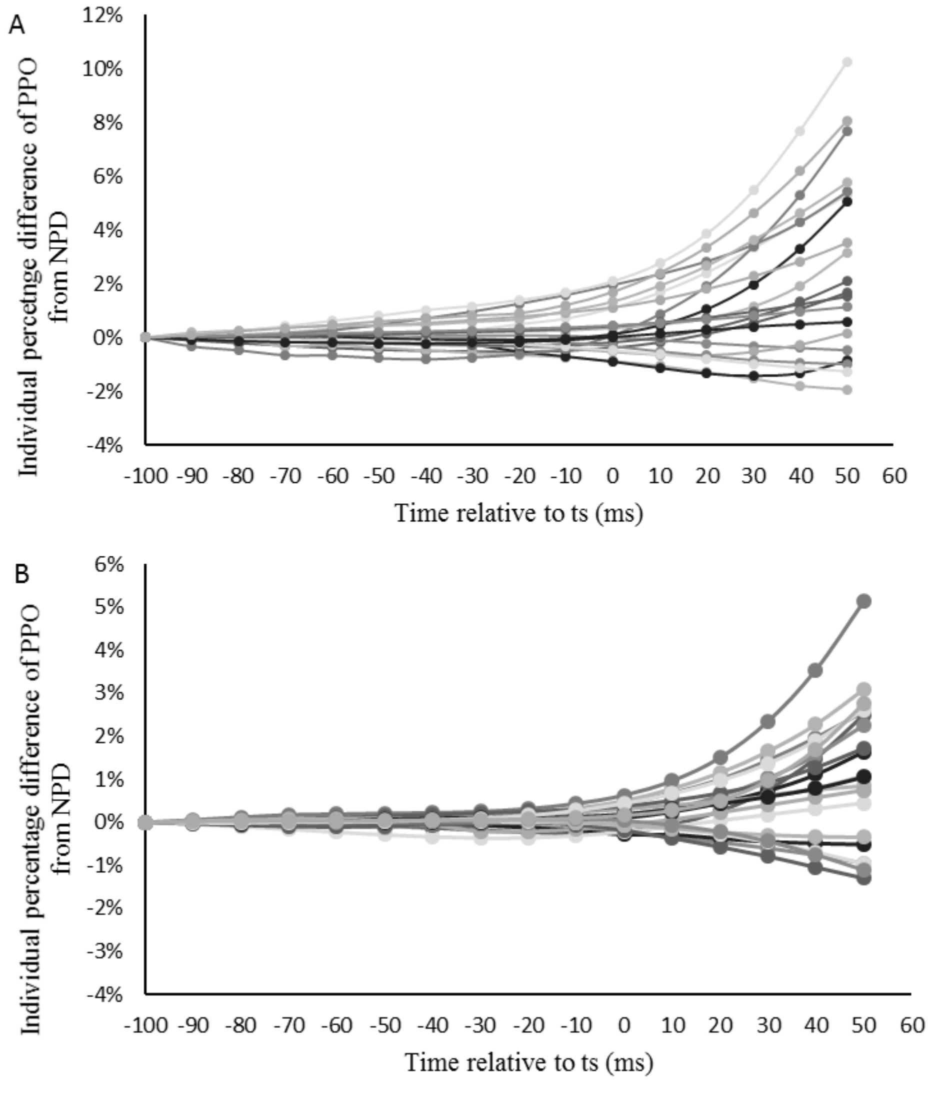

Figure 6. 2. Graph of the individual percentage difference of PPO from NPD, where A = Group 1 and B = Group 2

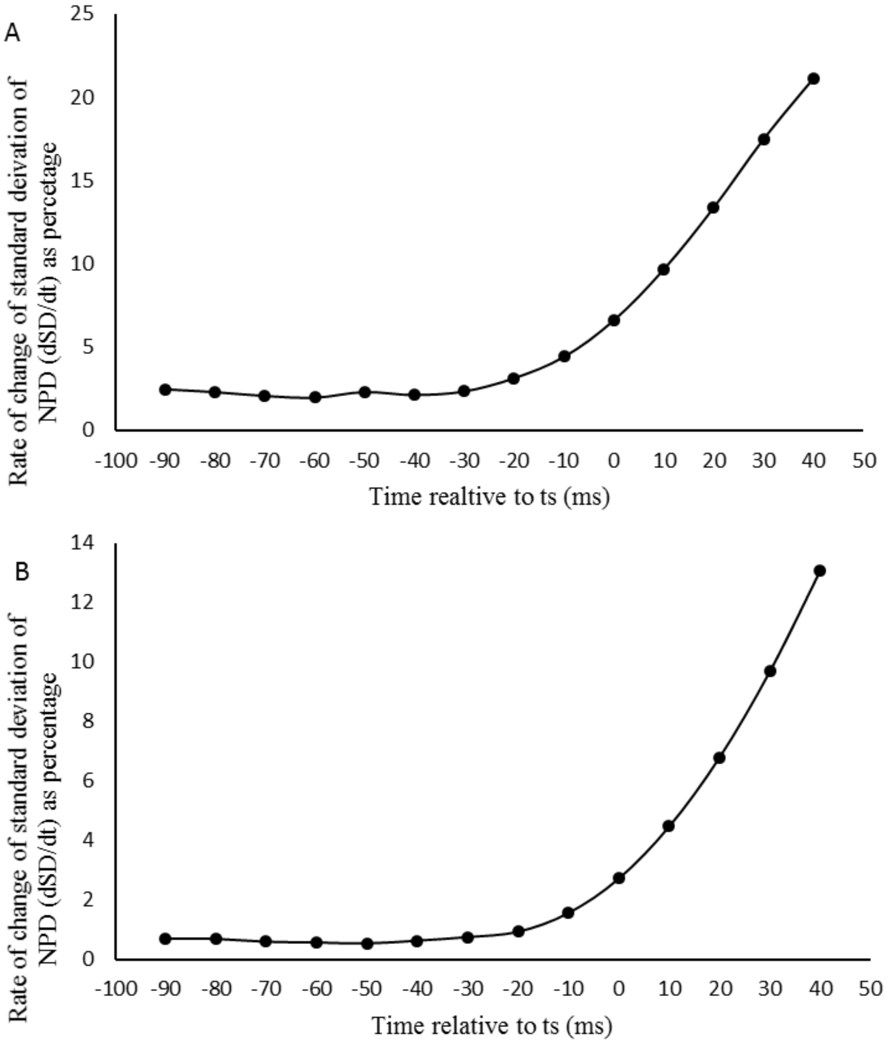

Figure 6. 3. Graph of the rate of change of the SD of NPD. Where A = Group 1 and B = Group 2

6.3.4 Selection of Sampling Frequency

The results of the sampling frequency comparisons can be seen in Figures 6.4, 6.5 and 6.6. The sampling frequency of 500, 250, 100, 50 and 10 Hz were compared with 1000 Hz. Table 6.5 summarises the mean difference, limits of agreement and ICC for each sampling frequency for Group 1 and Group 2.

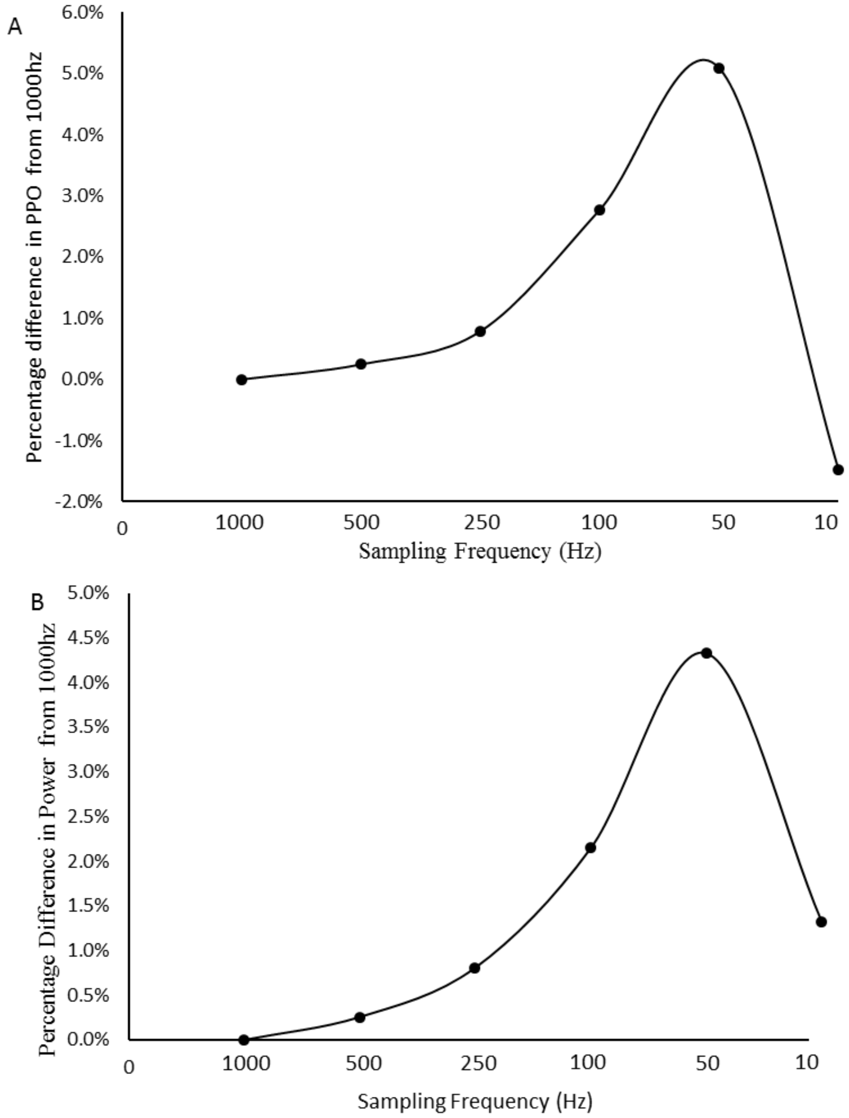

Figure 6. 4. Percentage difference in PPO from 1000 Hz for sampling frequencies 500, 250, 100, 50 and 10 Hz. Where A = Group 1 and B = Group 2

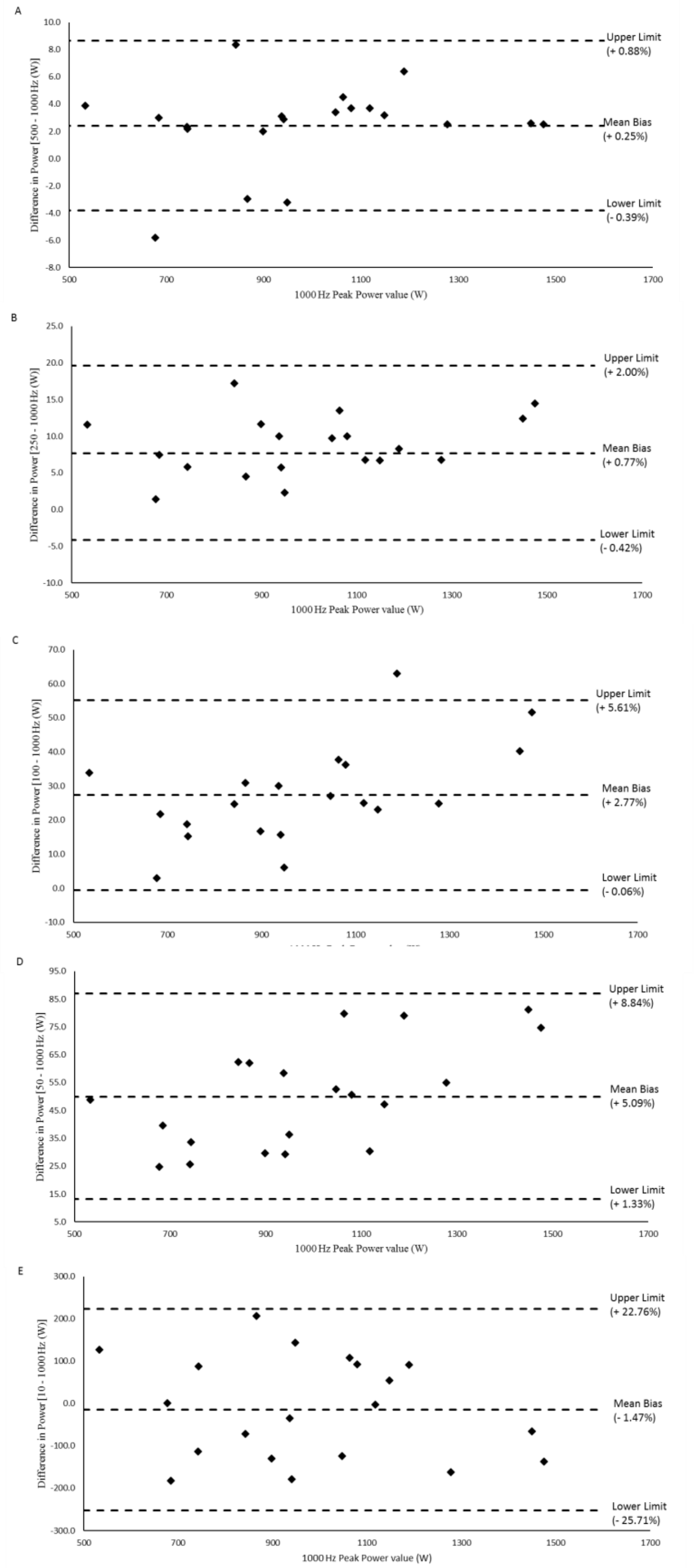

Figure 6. 5. Bland and Altman plot comparing peak vertical power outputs of countermovement jump using sampling frequencies of 500 Hz = A, 250 Hz = B, 100 Hz = C, 50 Hz = D and 10 Hz = E compared to 1000 Hz for Group 1

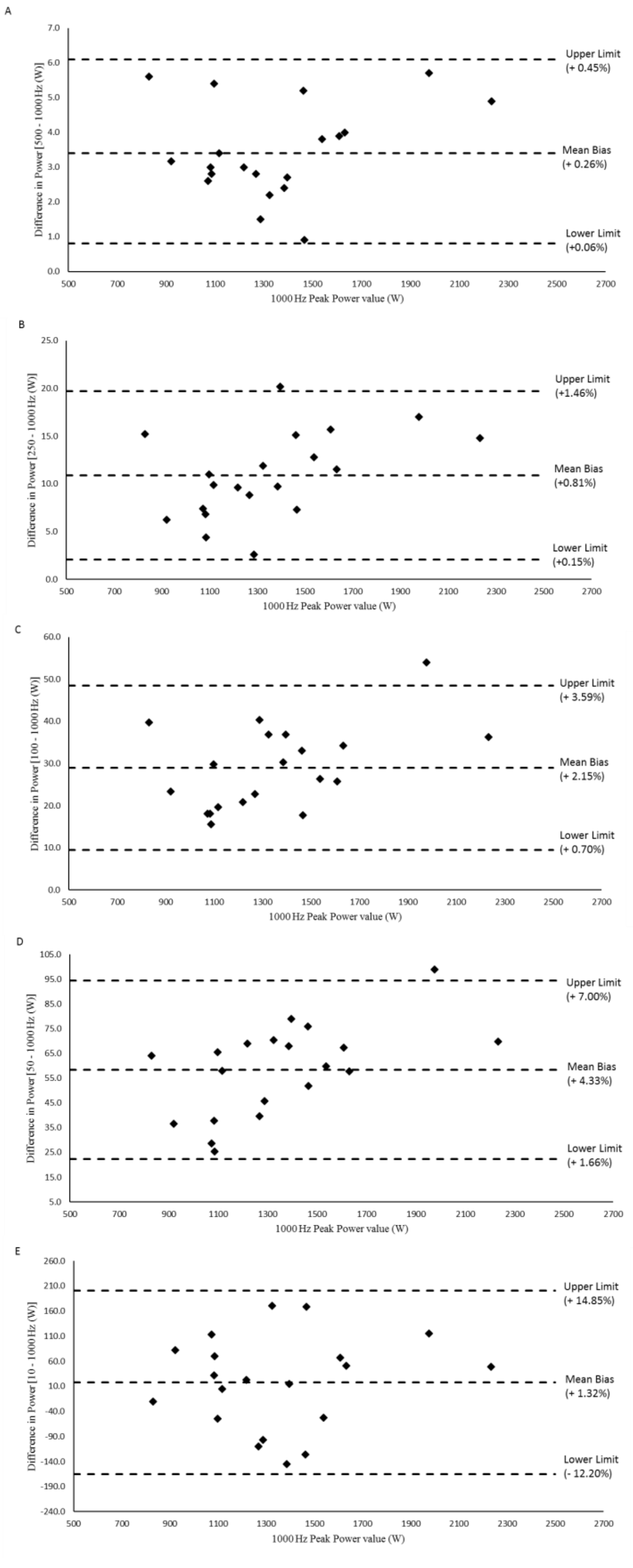

Figure 6. 6. Bland and Altman plot comparing peak vertical power outputs of countermovement jump using sampling frequencies of 500 Hz = A, 250 Hz = B, 100 Hz = C, 50 Hz = D and 10 Hz = E compared to 1000 Hz for Group 2

Table 6. 5. Mean difference, limits of agreement and ICC for sampling frequencies 500, 250, 100, 50 and 10 Hz compared with 1000 Hz for Group 1 and Group 2

	Sampling Frequency Comparison (Hz)	Mean difference in PPO (W)	Upper Limit of PPO (W)	Lower Limit of PPO (W)	ICC	P	r	R^2
Group 1	1000 / 500	2.4	8.7	-3.8	1	<0.0001	1	1.000
	1000 / 250	7.7	19.7	-4.2	1	<0.0001	1	1.000
	1000 / 100	27.3	55.2	-0.6	0.998	<0.0001	0.999	0.998
	1000 / 50	50.0	87.0	13.1	0.997	<0.0001	0.998	0.996
	1000 / 10	-14.5	223.8	-252.8	0.887	<0.0001	0.887	0.787
Group 2	1000 / 500	3.4	6.1	0.8	1	<0.0001	1	1.000
	1000 / 250	10.9	19.7	2.1	0.999	<0.0001	1	1.000
	1000 / 100	29.0	48.5	9.5	0.996	<0.0001	1	1.000
	1000 / 50	58.4	94.5	22.4	0.985	<0.0001	0.999	0.998
	1000 / 10	17.9	200.4	-164.7	0.966	<0.0001	0.967	0.935

Mean ± standard deviation

6.3.5 Method of Numerical Integration

The analysis resulted in a mean of the difference of 6.9 W for Group 1 and 7.5 W for Group 2 and limits of agreement (mean ± 1.96 SD) of 11.0 and 2.8 W for Group 1 and 11.9 and 3.1 W for Group 2.

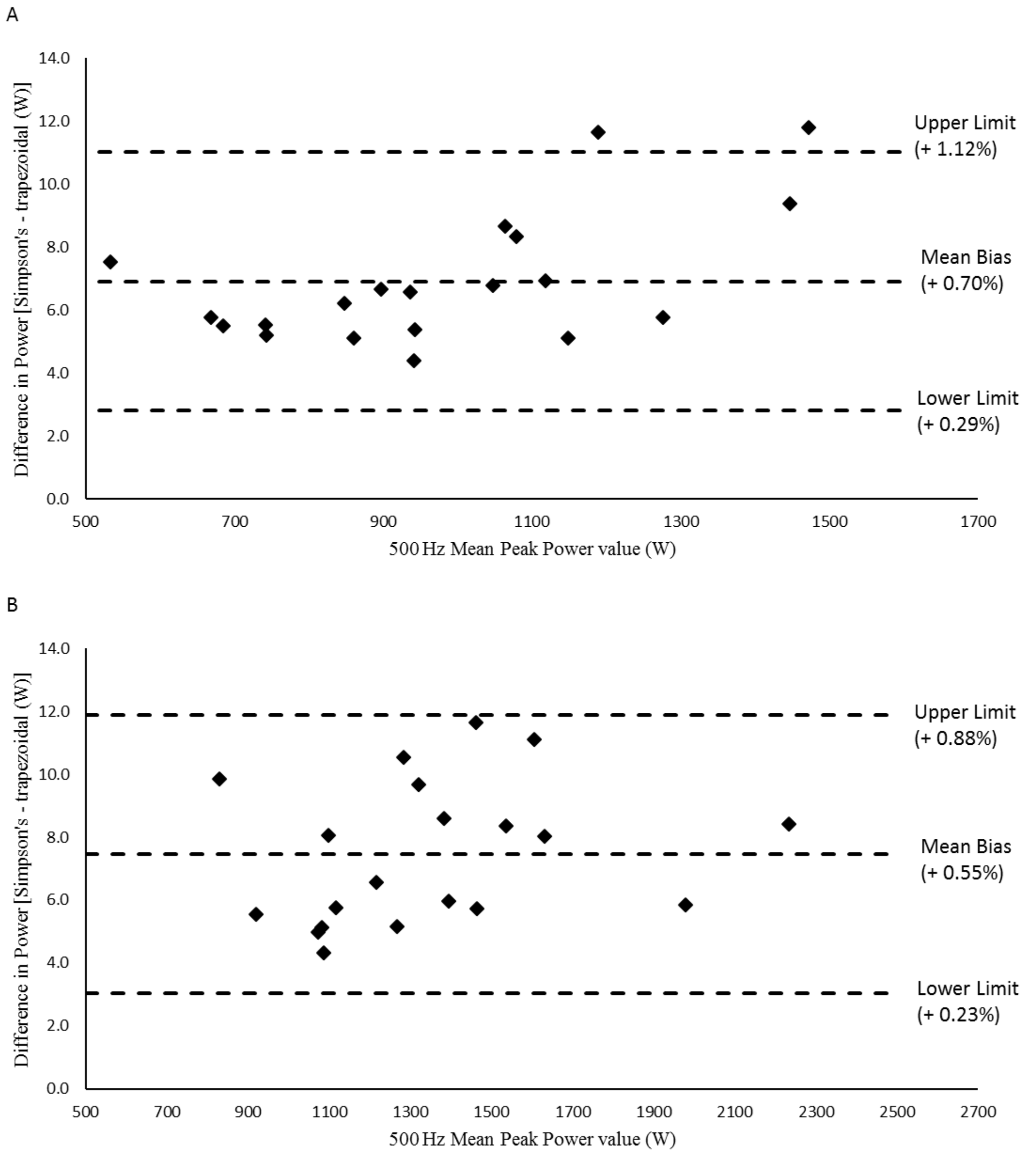

Figure 6. 7. Bland and Altman plot comparing peak vertical mechanical power outputs of countermovement jumps using Simpson's rule and Trapezoidal rule at a sampling frequency of 500 Hz. Where A = Group 1 and B = Group 2

6.3.6 Criterion Method

On the basis of these findings Tables 6.6 and 6.7 present the criterion method specifications for Group 1 and Group 2.

Table 6. 6. Group 1 criterion method specification for the measurement of peak mechanical power for in CMJ by the criterion force platform method

Variable	Criterion method specification
Vertical force range and resolution	6.7 x BW or higher at 12-bit (suggested) resolution or higher
Sampling and integration frequency	500 Hz or higher
Method of integration	Simpson's or Trapezoidal rule
Determination of body weight	Mean value of the vertical component of the mean ground reaction force measured for 1 second of the stationary stance phase immediately before the signal to jump
Determination of initiation of jump	The instant that BW ± 5 SD is exceeded after the signal to jump has been given minus 40 ms

Where BW = body weight and SD = standard deviation

Table 6. 7. Group 2 criterion method specification for the measurement of peak mechanical power for in CMJ by the criterion force platform method

Variable	Criterion method specification
Vertical force range and resolution	5.8 x BW or higher at 12-bit (suggested) resolution or higher
Sampling and integration frequency	500 Hz
Method of integration	Simpson's or Trapezoidal rule
Determination of body weight	Mean value of the vertical component of the mean ground reaction force measured for 1 second of the stationary stance phase immediately before the signal to jump
Determination of initiation of jump	The instant that BW ± 5 SD is exceeded after the signal to jump has been given minus 50 ms

Where BW = body weight and SD = standard deviation

6.4 Discussion

The purpose of this study was to establish a criterion protocol for the measurement of PPO produced during a CMJ using the FP method, for children aged 7 to 11 years. The criterion protocol was established using the key variables of vertical force range and resolution, force sampling frequency and resultant force integration frequency, method of integration, determination of bodyweight (BW) and the determination of the initiation of the jump. The results of this study identified specifications for seven variables which were used in conjunction, to reduce the error of deriving the CMJ output variable PPO and other variables. All specification were found to be lower than those found in the elite adult criterion method. Therefore, the null hypotheses can be rejected.

Body weight was determined by taking the mean VGRF value, as measured by the FP, for 1 second of the stance phase immediately before the signal to jump being given. Body weight has been well reported and the definition and measurement are considered standard. It is mutually defined as the mean of the period of 1 second during quiet standing with an associated uncertainty (Kibele, 1998; Owen et al., 2014). The BW (to 1d.p 1 digit), was unaffected by sampling frequency (1000, 500, 250, 100, 50 and 10 Hz) which replicates the findings of the Owen et al. (2014) in elite adults. The VGRF measured by a FP consists of the arithmetic sum of 4 individual vertical force signals originating from the 4 transducers of the platform. Therefore, combined gross vertical force and the individual vertical force transmitted through each corner transducer must be considered in order to not overload one of the vertical corner force transducers. Historically the VGRF range has been set in terms of BW. For example, in the method proposed by Kibele. (1998) the VGRF range was set as 3 - 3.5 x BW of the highest weighted participant tested. However, Owen et al. (2014) previously demonstrated that failure to consider corner component loads can lead to errors because of the range of individual force transducers being exceeded. Therefore, in the present study the VGRF range was established by the maximum value plus 3 SD of the VGRF signal from the corner transducer as proposed by Owen et al. (2014). This method identified a VGRF range setting of 6.7 x BW for Group 1 and 5.8 x BW for Group 2. The slight variations observed between the results of this study and the results presented by Owen et al. (2014) which reported a VGRF range selection of 5.6 x BW.

The difference in vertical force range selection may have occurred due to children aged 7 to 11 years having significantly smaller absolute BW and peak force (Fmax) values and significantly higher relative Fmax values when compared to elite adults in a CMJ via a FP. Though the selection of force range multiplying by BW is higher for Group 1 and Group 2 than the force range selection reported by Owen et al. (2014), the resulting absolute values of Group 1 and Group 2 will elicit a smaller VGRF range than the range needed for elite adults because they have lower BW as reported in *Experimental Chapter 1*. This is believed to reason why there are differences Group 1 and Group 2 selection of the vertical force range as *Experimental Chapter 2* highlighted that children in school years 5 and 6 (Group 2) had significantly greater absolute BW and Fmax CMJ values than children in school years 3 and 4 (Group 1).

A wide variety of invalid methods have been used to determine the instant when a CMJ has been initiated within the literature. Many studies determine the instant when a CMJ has been initiated as, when the CMJ F/T history drops below a threshold such as 5% of BW (Cormack et al., 2008; Hori et al., 2009; Sheppard, Doyle, et al., 2008) or "about one SD of BW" (Focke et al., 2013) during the stance phases and define the jump initiation as the instant that the VGRF falls below that threshold. Others qualitatively assess where the jump has started by manually inspecting the force-trace (Hanson, Leigh, Mynark, Hanson S Leigh, & Mynark, 2007) or refer to software but do not describe the methods (Amonette et al., 2012; Hertogh & Hue, 2002). There is only one validated method within the literature for determining the instant when a CMJ has been initiated (BW ± 5SD – 30 ms) (Owen et al., 2014), which was developed to minimise the uncertainty in PPO, by identifying an instant when the entire jump signal was retained but none of the stance phase. Figure 6.3 highlights the determination of the initiation of jump to be the instant BW ± 5SD – 50 ms for Group 1 and BW ± 5SD – 40 ms for Group 2. The reason for differences observed between the findings of Group 1, Group 2 and that of Owen et al. (2014) is currently unclear. The determination of initiation of the jump phase is population specific, which may result in subtle difference between the methods. For example, the increase in the VGRF at the CMJ initiation was only found in 25% of the jumps for Group 2, whereas the increase in the VGRF at the CMJ initiation was for 50% participants for Group 1, which was also reported in the findings by Owen et al. (2014). The rate of change of uncertainty for measuring PPO was amplified significantly if the initiation of the CMJ was identified late. Whereas, if the rate of change of uncertainty for measuring PPO was unaffected if the initiation of the CMJ was identified early the rate of change of uncertainty for measuring PPO was unaffected. However, identifying the initiation of the CMJ early will result in errors due unbalanced impulses in the analysis.

When sampling a signal in order to represent it elsewhere, the higher the sampling frequency the greater the fidelity of the representation of the original signal (Owen et al., 2014). Specifically, Nyquist's sampling theorem (Nyquist, 1928) states that a sampling frequency of at least double the highest frequency contained in the signal is necessary to ensure that none of the original signal is lost during the sampling process and also to prevent aliasing. In human locomotion the highest frequency is less than 10 Hz, so a 20 Hz sampling rate should be satisfactory however, in reality a F/T history cannot be represented by a function and is non-cyclical and as such is not suitable for this type of analysis (Owen et al., 2014; Robertson, Caldwell, & Hamill, 2013). Sampling frequency of 1000 Hz for elite adults is typically used within biomechanics (Bevan et al., 2009; Hanson et al., 2007; Kibele, 1998) as it produces more accurate results than lower sampling frequencies such as 500, 100 Hz (Owen et al., 2014). Pilot data highlighted there was no significance difference between 2000 and 1000 Hz and previous data has highlighted a 1000 Hz as the gold standard, therefore there would be no need to sample at 2000 Hz. A minimum sampling frequency of 500 Hz or higher was identified for Group 1 and Group 2, whereas the finding of Owen et al. (2014) required a 1000 Hz for elite adults. The differences may be as a result of children have significantly lower absolute values of BW, Fmax and basic rate of force development (BRFD) when performing a CMJ via a FP. Nonetheless, a minimum of 500 Hz is still required, potentially due to normative and allometric values for Fmax and BRFD being much higher in children aged 7 to 11 years when compared to elite adults as releveled in a pilot study. Figure 6.4 initially highlights that a sampling frequency of 10 Hz is better than sampling frequencies of 250, 100 and 50 Hz. However, Table 6.5, Figure 6.5 and Figure 6.6 reveals that the sampling frequency of 10 Hz has a considerably large range between the upper and lower limits of agreement with a number of negative values has reduced the percentage difference values rather than increase them.

Figure 6.7 identifies the mean difference for the determination of peak power between the Simpson's and Trapezoidal rule for Group 1 (+ 0.70%) and Group 2 (+ 0.55%). There was no significant difference in output values when using the Trapezoidal or Simpson's rule as the method of integration, in conjunction with the findings of Owen et al. (2014). It is currently unknown what method of numerical integration best represents the CMJ F/T history despite several error analyses used at different sampling frequencies. This study did not investigate the effect of ADC resolution on PPO because it is not adjustable in commercial systems. However, Table 6.4 presented a number of different resolution accuracies based on selection of the vertical force range minimum, average and maximum values. A 12-bit range or higher was suggested for Group 1 and Group 2 as the accuracy would be under 1 N based on the force range selection of the participants in this study. However, in practice, the resolution of the system is dependent on other factors in addition to ADC bits, including system noise and actual force range as opposed to stated maximum range. The method proposed by Owen et al. (2014) identified a 16-bit resolution, however, the VGRF ranges in a CMJ are much higher in elite adults and thus require a higher resolution.

6.5 Conclusion

This study has achieved the third objective of this thesis which was to establish a criterion protocol for the measurement of PPO produced during a CMJ using the FP method, for children aged 7 to 11 years. The criterion protocol was established using the key variables of vertical force range and resolution, force sampling frequency and resultant force integration frequency, method of integration, determination of bodyweight (BW) and the determination of the initiation of the jump. Specifically, this study answered several research questions, highlighting that the criterion methods described in this study should be used for future use when measuring CMJ performance on a FP in children aged 7 to 11 years. Subtle differences in the developed criterion methods when compared to the EACM will result in cheaper equipment due to lower specification and therefore greater availability and application of the accurate assessment of neuromuscular performance children in children aged 7 to 11 years will take place. Furthermore, a method of estimating PPO in children aged 7 to 11 for practitioners who do not have access to force platforms.

Thesis Map

Chapter 4: Experimental Study 1: The Effect of Age and Sex on Countermovement Jump Kinetics between Children Aged 7 to 11 Years and Elite Adults	
Objective	To investigate the effect of age and sex on absolute unprocessed countermovement jump (CMJ) variables between children aged 7 to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children
Key Findings	Significant age differences occurred between elite adults and children aged 7 to 11 years, with elite adults having significantly higher CMJ kinetic values ($p \leq 0.05$). No significant sex differences were observed in the child group ($p > 0.05$), whereas significant sex differences were observed between elite adults with males having significantly larger values ($p \leq 0.05$)
Chapter 5: Experimental Study 2: The Effect of Body Size on Countermovement Jump Kinetics in Children Aged 7 to 11 Years	
Objective	To investigate the importance of accounting for body size in their interpretation of countermovement jump kinetics in children aged 7 to 11 years
Key Findings	Significant age differences occurred for absolute CMJ variables for school years 3 and 4 to years 5 and 6 ($p > 0.05$). No significant age or sex differences were observed for normalised or allometrically scaled values ($p > 0.05$). No significant sex differences were observed for any absolute CMJ variables ($p > 0.05$)
Chapter 6: Experimental Study 3: Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump for Children Aged 7 to 11 Years	
Objective	To establish a criterion protocol for the measurement of lower body instantaneous peak mechanical power output (PPO) and other CMJ variables using the force platform criterion method for children aged 7 to 11 years
Key Findings	Two new specifications have been established as the only valid methods for measuring PPO and other processed CMJ variables when using a force platform for measuring human performance in children aged 7 to 11 years
Chapter 7: Experimental Study 4: The Development of Regression Equations to Estimate Peak Mechanical Power Output in Children Aged 7 to 11 Years	
Objective	To use regression analysis to estimate of lower body peak mechanical power output in children aged 7 to 11 years
Key Findings	

Chapter 7 Experimental Study 4: The Development of Regression Equations to Estimate Peak Mechanical Power Output in Children Aged 7 to 11 Years

7.1 Introduction

Experimental Chapter 3 developed two criterion methods for assessing lower body peak mechanical power output (PPO) from a countermovement jump (CMJ) performed on a force platform (FP) in children aged 7 to 11 years. This achieved the first part of the overall aim of this thesis. The second part of the overall aim of this thesis sought to develop prediction equations for estimating PPO in the field for children aged 7 to 11 years. The rationale for including this was because the use of measuring a CMJ via FP are typically restricted to laboratory settings or facilities with large budgets (Duncan, Hankey, & Nevill, 2013). Even though the develop criterion methods have established lower specifications which would result in cheaper equipment, an alternative cheaper method of attaining PPO should be developed for those unavailable to utilise a FP. The use of regression equations has been previously used to estimate PPO in adult, adolescence and child populations as they can be estimated easily measured variables in the field such as body mass, stature and flight height. However, as previously stated many of the developed and proposed regression equations have been developed from adult heights and weights and thus unsuitable for use in children. Therefore, the objective of *Experimental Chapter 4* was to use regression analysis to estimate of lower body peak mechanical power output in children aged 7 to 11 years. This can be achieved by addressing the research question:

Can lower body peak mechanical power output be estimated as function of easily measured variables in the field in children aged 7 to 11 years?

The null hypotheses of *Experimental Chapter 4* is that PPO cannot be estimated by easily measured variables in children aged 7 to 11 years.

7.2 Methodology

7.2.1 Participants

Force-time (F/T) histories were collected for 851 UK primary school children each performing one CMJ with arms akimbo. Participants were grouped by their corresponding school years 3, 4, 5 and 6 and by sex (Table 7.1).

7.2.2 Measurements

The F/T histories were used to determine body weight (BW), body mass (BM) and lower body instantaneous peak mechanical power output (PPO) utilising the two criterion methods established in *Experimental Chapter 3*. The F/T history was then resampled at 100 Hz and flight height (FH) was determined via the flight-time method to replicate the collection of data from a jump mat.

Determination of Regression Variables

The variables used in the regression analysis were FH (m) estimated from flight-time, body mass (kg) and stature (m). Theses variable were chosen as they can be measured easily and accurately within a field based setting.

Measurement of Flight Height

Vertical flight displacement was determined via jump flight-time method (Kibele, 1998). Each F/T history was resampled to 100 Hz to replicate the measurement of FH via cheaper, more readily available, devices such as jump mats. If the whole body centre of gravity (CoG) remains in the same position for take-off and landing then an estimate of FH (height gained by CoG after take-off) is given by:

$$(1) \qquad FH = \frac{1}{8} \cdot g \cdot T^2$$

Whereby FH = flight height (m), T= total flight-time (s) and g = acceleration due to gravity of the earth (9.81 m.s^{-2})(Kibele, 1998).

The duration of the flight phase of a countermovement jump was determined from vertical F/T history, providing a measure of flight-time of the jump attained from the landing time (T_{td}) taken from take-off time (T_{to}). Tto is consisted to be the instant when the toes leave the FP and T_{td} is considered to be the instant when the toes touch the FP. A validated criterion method by Walters. (2017) was used to determine T_{to} and T_{td} in order to avoid a miss-trigger and incorrect identification of T_{to} and T_{td}. T_{to} was determined as the first time point at which all of the following criteria were met: (i) must be after the start of the concentric phase of the jump; (ii) the force negatively crosses 5N; (iii) the average force of the next 9 sample forces and the original force (making 10 sample forces) < 2SD of the average force during the unloaded phase (flight). If the criteria were not met, the sequence was repeated on the next sample (x+1) and so on until all of the criteria were met (Walters, 2017). T_{td} was determined as the first point at which all of the following criteria were met : (i) had to occur after the point identified as take-off time; (ii) the force (at that time) was > 5N and the following ten samples averaged a force greater that 5SD of the average force during the unloaded phase (flight of participants). If the criteria were not met at time point 'x', the steps were reapplied at 'x+1' until all criteria were met (Walters, 2017).

Measurement of Lower Limb Peak Mechanical Power

The variable PPO was determined from VGRF of the countermovement jump in conjunction with the participant's bodyweight and body mass to determine the instantaneous velocity and displacement of the CoG (Hatze, 1998). Instantaneous power was determined using the following standard relationship:

$$P = F \cdot v$$

Equation 3

Whereby P = mechanical power output (W), F = force (N) v = velocity (m.s^{-1})

To determine the velocity of an individual's CoG, numerical integration was performed using Simpson's rule with intervals equal to the sample width. Before the calculation of the strip area, the participant's body weight was subtracted from the VGRF values. The area of the strip, with width equal to the sample period, then represented the impulse for that time interval. Using the relationship that impulse equals change in momentum, the strip area was then divided by the participant's body mass to produce a value for the change in velocity for the CoG (it was assumed that the participant's mass remained constant throughout the jump). The change in velocity was then added to the CoG previous velocity to produce a new velocity at a time equal to that particular interval's end time. This process was continued throughout the jump. As this method can only determine the change in velocity, it was necessary to know the velocity of the CoG at some point in time. For this purpose, the velocity of the CoG was taken to be zero before the initiation of the jump (during the period of quiet standing), specifically at the point identified as the start of the jump. The start point was defined as the time when the participant's ground reaction force exceeded the mean ± 5 SD from the values obtained in the second (of the stationary body mass measuring phase) immediately before the command to jump, in a fashion similar to Vanrenterghem, De Clercq & Van Cleven. (2001). Integration started from this point (West et al., 2011). BW ± 5SD was chosen as the start point due to variation in the measurement of the body weight of a participant at rest on a FP. This is due to system noise and slight vertical oscillation of the whole body CoG due to breathing and pendular swing of the whole body CoG over the feet in order to actively maintain balance (Owen, 2008). To identify when the body weight of the participant has changed beyond normal variation, a threshold level of normal variation needs to be established, BW ± 5SD – 50 ms for school year 3 and 4 and BW ± 5SD – 40 ms were chosen to reduce the probability of an erroneous initiation of integration start time ($p = 2x10^{-9}$as reported in *Experimental Chapter 3*.

7.2.3 Statistical Analysis

Following identification of normality and homogeneity of variance, a linear regression and multiple regression was performed using SPSS software (Version 22; SPSS Inc., Chicago, IL), with significance set at $p \leq 0.05$. The predictor variables initially used were BM, FH and stature. Preliminary linear regression models were run to determine whether the predictor variables significantly improved the fit of the regression model. If the predictor variables did not significantly improve the regression model they were removed from the model and future analysis. Significant predictor variables (BM and FH) were subsequently used to produce 8 multiple regression models according to school year and sex. A correlation matrix was produced for the significant predictor variables and outcome variables, to determine the order in which the predictor variables were entered into the regression model. The highest correlated predictor variable was entered first and the lowest predictor variable added to the model last. To fit and cross validate the models, a random two-third split of the data was used for each year group and sex. The remaining one-third of the data was used to determine the validity of the linear model by performing t-tests to determine if there was a significant difference between the predicted and criterion PPO of the cross validation group. If there were no significant differences between criterion and predicted measures of PPO in the cross validation group, the two groups were combined and a multiple regression equation was determined from the combined group for each year group and sex. Data is presented as mean ± standard deviation.

7.3 Results

Participant anthropometric data are presented in Table 7.1.

Table 7. 1. Anthropometric data by year group

Group/ Model	N	Sex	School year	Age (year)	Stature (m)	Body mass (kg)
1	96	Male	3	7.92 ± 0.37	1.35 ± 0.21	29.5 ± 7.8
2	110	Female	3	7.91 ± 0.35	1.36 ± 0.16	28.7 ± 6.1
3	102	Male	4	8.96 ± 0.36	1.41 ± 0.16	32.5 ± 7.8
4	98	Female	4	8.95 ± 0.43	1.38 ± 0.16	30.4 ± 7.6
5	113	Male	5	9.95 ± 0.43	1.39 ± 0.10	38.1 ± 10.2
6	115	Female	5	9.96 ± 0.52	1.37 ± 0.21	36.1 ± 9.3
7	104	Male	6	10.8 ± 0.50	1.45 ± 0.14	39.9 ± 9.1
8	113	Female	6	10.88 ± 0.35	1.41 ± 0.20	40.8 ± 10.5

Mean ± standard deviation

Stature was found to have no significant effect on the preliminary model ($p > 0.05$) for year group and was removed from further analysis. Table 7.2 shows correlations between significant predictor variables and the outcome variable.

Table 7. 2. Correlation matrix (Pearson r) for predictor and outcome variables for entire data set

	Peak Power	Body Mass	Flight Height
Peak Power	1.00	0.821*	0.226*
Body Mass	0.821*	1.000	-0.114*
Flight Height	0.226*	-0.114*	1.000

*Note * Significance level for all correlation coefficient is p < 0.05*

Table 7.3 presents the criterion peak power and the predicted peak power output for the cross validation group with no significant differences between the criterion and predicted peak power for any group or sex.

Table 7. 3. Cross validation group results

School Year (sex)	N	Criterion Peak Power Output (W)	Predicted Peak Power Output (W)	P
3 (Male)	33	888 ± 196	885 ± 190	p = 0.746
3 (Female)	37	923 ± 230	929 ± 153	p = 0.748
4 (Male)	34	1000 ± 249	1037 ± 203	p = 0.119
4 (Female)	33	1061 ± 247	1035 ± 220	p = 0.193
5 (Male)	32	1299 ± 276	1267 ± 232	p = 0.265
5 (Female)	37	1245 ± 306	1259 ± 223	p = 0.668
6 (Male)	35	1417 ± 297	1406 ± 296	p = 0.659
6 (Female)	38	1351 ± 357	1333 ± 259	p = 0.606

Mean ± standard deviation

Table 7.4 shows the regression equations for estimating peak by year group and sex. All regression equations PPO group means had an associated standard estimate of error (SEE) from 9.6-15.1% of the mean (102-177 W SEE), R^2 value from 0.781-0.837 ($p < 0.05$). Table 7.5 highlights the overall group criterion peak power and predicted peak power from the developed regression equation for each year group and sex (Equation 7.1-7.8), with scatter graph plots of criterion peak power versus predicted peak power for males (Figure 7.1) and females (Figure 7.2) highlighted.

Table 7. 4. Regression equation for estimating peak vertical mechanical power of the whole body centre of gravity for a countermovement jump by school years and sex

School Year (Sex)	r (R^2)	SEE (W) [% of mean]	P (F)	Regression
3 (Male)	0.882 (0.778)	102 [11.4%]	P<0.0001 (162.0)	7.1: P_{pest}(W) = [BM (kg) x 24.5] + [FH (m) x 1423.9] -16.5
3 (Female)	0.846 (0.716)	102 [11.0%]	P<0.0001 (134.5)	7.2: P_{pest}(W) = [BM (kg) x 26.7] + [FH (m) x 1945.7] -108.2
4 (Male)	0.852 (0.726)	102 [9.6%]	P<0.0001 (130.6)	7.3: P_{pest}(W) = [BM (kg) x 24.8] + [FH (m) x 1763.1] -15.1
4 (Female)	0.781 (0.610)	155 [15.1%]	P<0.0001 (74.31)	7.4: P_{pest}(W) = [BM (kg) x 25.4] + [FH (m) x 985.9] + 107.0
5 (Male)	0.820 (0.672)	161 [12.8%]	P<0.0001 (113.1)	7.5: P_{pest}(W) = [BM (kg) x 23.5] + [FH (m) x 1994.4] + 24.4
5 (Female)	0.847 (0.717)	157 [12.7%]	P<0.0001 (142.7)	7.6: P_{pest}(W) = [BM (kg) x 28.0] + [FH (m) x 1249.7] + 26.6
6 (Male)	0.915 (0.837)	136 [9.8%]	P<0.0001 (260.7)	7.7: P_{pest}(W) = [BM (kg) x 34.2] + [FH (m) x 3377.4] -589.5
6 (Female)	0.829 (0.687)	177 [13.1%]	P<0.0001 (120.4)	7.8: P_{pest}(W) = [BM (kg) x 25.5] + [FH (m) x 1964.9] -54.5

Note SSE= Standard error of estimate (W), BM = Body mass (kg) and FH = flight height

Table 7. 5. Countermovement jump variables flight height, criterion peak power output and predicted peak power output

Regression model	N	School Year (sex)	Flight Height (m)	Criterion Peak Power Output (W)	Predicted Peak Power Output (W)
7.1	96	3 (Male)	0.14 ± 0.49	901 ± 214	901 ± 189
7.2	110	3 (Female)	0.14 ± 0.40	933 ± 190	933 ± 160
7.3	102	4 (Male)	0.16 ± 0.50	1067 ± 233	1067 ± 199
7.4	98	4 (Female)	0.15 ± 0.51	1029 ± 245	1029 ± 191
7.5	113	5 (Male)	0.17 ± 0.56	1265 ± 279	1265 ± 229
7.6	115	5 (Female)	0.17 ± 0.50	1245 ± 294	1245 ± 249
7.7	104	6 (Male)	0.18 ± 0.50	1395 ± 336	1395 ± 308
7.8	113	6 (Female)	0.16 ± 0.56	1351 ± 313	1351 ± 259

Mean ± standard deviation

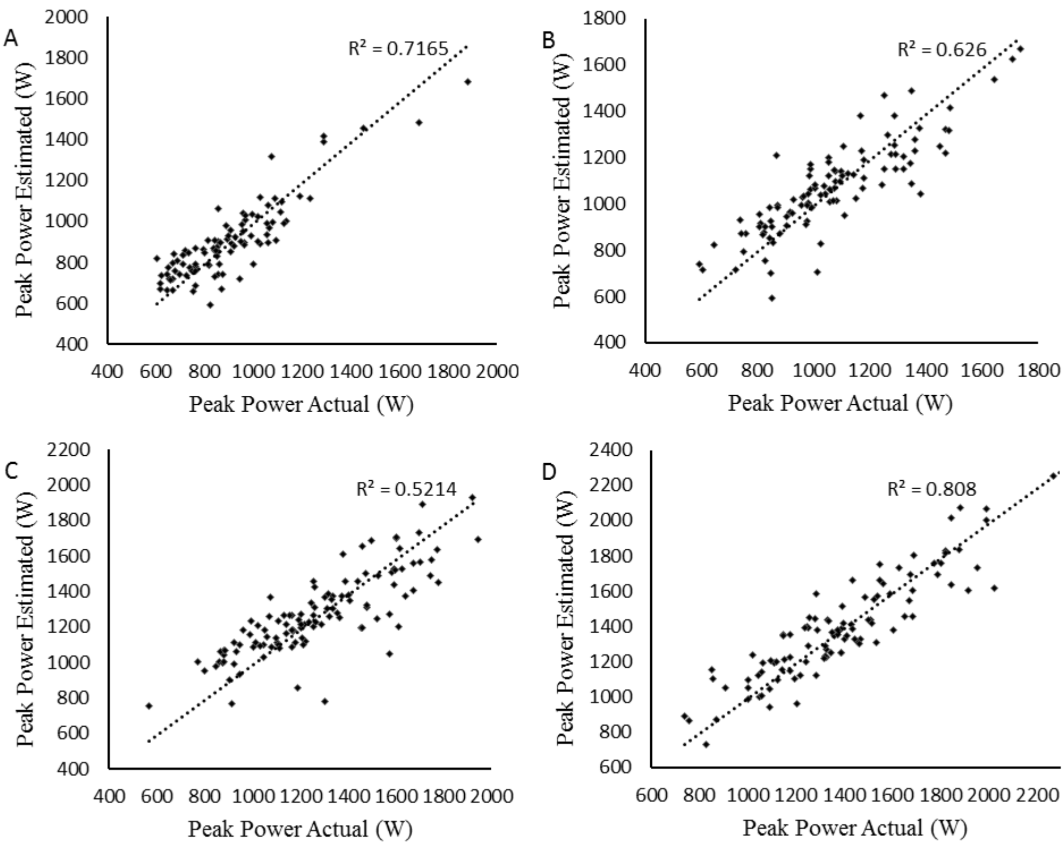

Figure 7. 1. Scatter graphs of criterion peak power and estimated peak power. Where A = year 3 male, B = year 4 male, C = year 5 male, and D = year 6 male

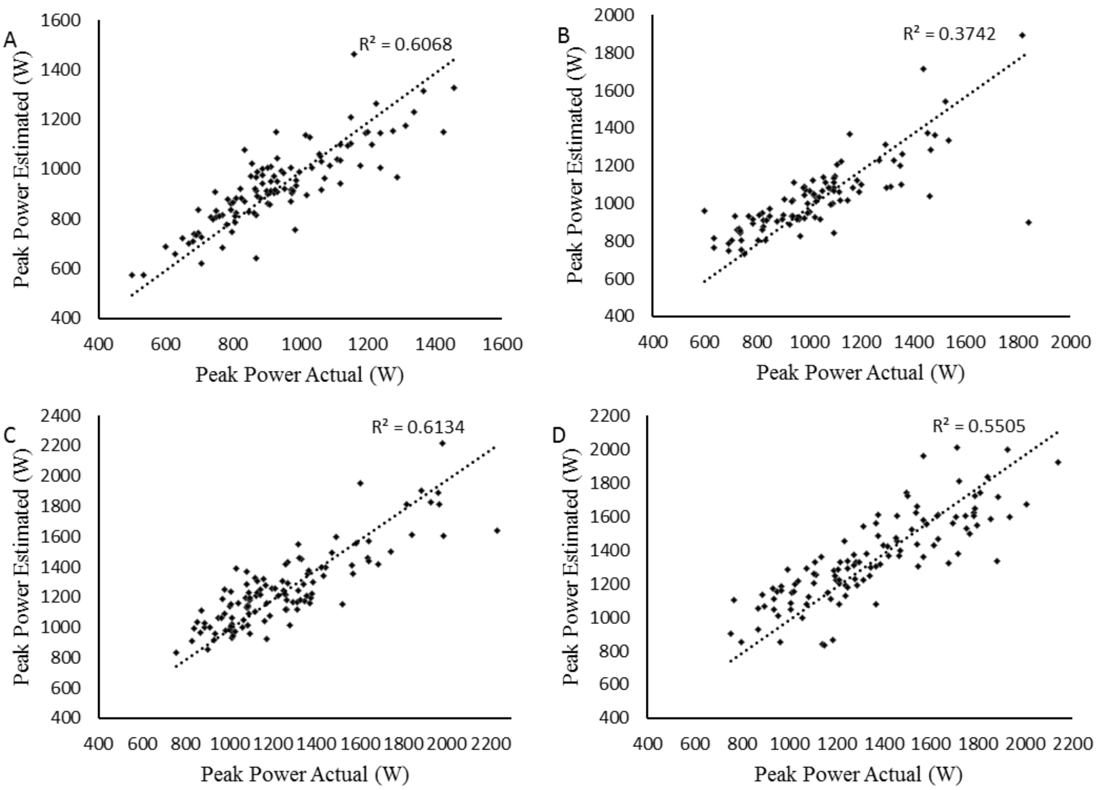

Figure 7. 2. Scatter graphs of criterion peak power and estimated peak power. Where A = year 3 female, B = year 4 female, C = year 5 female, and D = year 6 female

7.4 Discussion

The purpose of this study was to use regression analysis to estimate of lower body peak mechanical power output in children aged 7 to 11 years. The results of this study highlight that stature did not have a significant effect on the regression models whilst BM had the highest positive correlation with criterion PPO (r = 0.821) and FH (0.226). This is in accord with Sayers et al, (1999) who utilised BM and jump height or flight height depending on the equipment used to measure CMJ performance. The cross-validation demonstrated no significant difference and a high correlation between criterion and estimate PPO. The regression models present high positive correlation with the criterion PPO value, predicting 61% - 84% of the variance in the criterion PPO. Therefore, the null hypotheses could be rejected.

Criterion PPO and estimated PPO for each year and sex group are presented in Table 7.5, though comparisons of the findings are limited as no regression models have previously been developed or utilised for primary school children, in addition to inconsistency in reporting the results of the adult regression models. The studies that utilised the same variables body mass and jump height for their regression equations demonstrated, SEE of 462 W (R^2 = 0.91) for predicting PPO in college athletes (D. L. Johnson & Bahamonde, 1996), SEE of 561 W (R^2 = 0.78) for predicting PPO in adults (Sayers et al., 1999) and SSE of 250 W (R^2 = 0.92) for predicting PPO in 415 adolescent male athletes (Amonette et al., 2012). The results of this study indicate that the regression models developed are valid for estimating PPO group means with an associated standard estimate of error (SEE) all regression models ranging from 9.6-15.1% of the mean (SEE = 102-177 W, R^2 = 0.61 - 0.84) (Table 7.4). When compared to previous regression models reported within the literature for predicting PPO the results of this study demonstrated a lower percentage of variance and SEE (Amonette et al., 2012; Canavan & Vescovi, 2004; Harman, Rosenstein, Frykman, Rosenstein, et al., 1991; Hertogh & Hue, 2002; D. L. Johnson & Bahamonde, 1996; Lara et al., 2006; Sayers et al., 1999; Shetty, 2002). A potentially reason for the higher percentage of variance and SEE seen within the literature could be attributed to the lack of validity for determining actual PPO for example, no information about the definition of the jump initiation time or method of integration used to determine instantaneous vertical velocity of the CoG in a CMJ was reported in any of the studies for the measurement of actual PPO (Owen, 2008). This could subsequently produce greater error in attaining actual PPO and therefore, affect the variance and SEE of the regression models used to predict PPO.

Previous research has demonstrated that regression equations are poor methods of assessing predicted PPO for performance, fatigue or recovery of an individual, as the errors may exceed 50% (Amonette et al., 2012; Quagliarella, Sasanelli, Belgiovine, Moretti, & Moretti, 2011). Nonetheless, such regression models are useful for group comparisons (Quagliarella et al., 2011). Duncan, Hankey & Nevill. (2013), identified that actual PPO varied according to sex and age in children and that specific equations should be developed, though how this is achieved requires further investigation. For example, a child could be represented by chronological age, maturation status or school year. Recent trends have used the concept of bio-banding to group children undertaking physical competitions by maturation status rather than chronological age and school year (Cumming, Brown, et al., 2017; Cumming, Lloyd, Oliver, Eisenmann, & Malina, 2017). Though limitations are associated with each method. This study investigated and suggested representing children aged 7 to 11 years by school year.

The rationale for this was that if chronological age was selected two children born on the 31st of August and 1st of September may have different neuromuscular performance scores due the older child having engaged in one year more of formal physical literacy and extracurricular physical activities than the younger child. Furthermore, a child with a chronological age of 12 years but a maturation status of 14 year old child could be grouped with other 14 year old children. However, the children with a chronological age of 14 would have been exposed to an additional 2 years of formal physical literacy, extracurricular physical activities and cognitive development which would impact upon the neuromuscular performance of the child.

7.5 Conclusion

This study has achieved the fourth objective of this thesis which was to use regression analysis to estimate of lower body peak mechanical power output in children aged 7 to 11 years. Specifically, this study answered one research question, by presenting a number of regression equations (Table 7.4) that have been developed for estimating PPO in primary school children aged between 7 and 11 years. These equations are applicable to use within the field with less costly and more accessible equipment such as body mass scales and a jump mat or smart phone application with a flight-time measurement application installed to accurately estimate group mean PPO in children. Finally the present results provide normative values for PPO in primary school children. Future research should focus on the comparison of commonly used regression equation against the regression developed here for children to identify and validate the best equation to estimate PPO for group means and normative data in primary school children.

Thesis Map

<table>
<tr><td colspan="2">Chapter 4: Experimental Study 1: The Effect of Age and Sex on Countermovement Jump Kinetics between Children Aged 7 to 11 Years and Elite Adults</td></tr>
<tr><td>Objective</td><td>To investigate the effect of age and sex on absolute unprocessed countermovement jump (CMJ) variables between children aged 7 to 11 years and elite adults to determine whether the current elite adult criterion method should be re-evaluated for children</td></tr>
<tr><td>Key Findings</td><td>Significant age differences occurred between elite adults and children aged 7 to 11 years, with elite adults having significantly higher CMJ kinetic values ($p \leq 0.05$). No significant sex differences were observed in the child group ($p > 0.05$), whereas significant sex differences were observed between elite adults with males having significantly larger values ($p \leq 0.05$)</td></tr>
<tr><td colspan="2">Chapter 5: Experimental Study 2: The Effect of Body Size on Countermovement Jump Kinetics in Children Aged 7 to 11 Years</td></tr>
<tr><td>Objective</td><td>To investigate the importance of accounting for body size in their interpretation of countermovement jump kinetics in children aged 7 to 11 years</td></tr>
<tr><td>Key Findings</td><td>Significant age differences occurred for absolute CMJ variables for school years 3 and 4 to years 5 and 6 ($p > 0.05$). No significant age or sex differences were observed for normalised or allometrically scaled values ($p > 0.05$). No significant sex differences were observed for any absolute CMJ variables ($p > 0.05$)</td></tr>
<tr><td colspan="2">Chapter 6: Experimental Study 3: Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump for Children Aged 7 to 11 Years</td></tr>
<tr><td>Objective</td><td>To establish a criterion protocol for the measurement of lower body instantaneous peak mechanical power output (PPO) and other CMJ variables using the force platform criterion method for children aged 7 to 11 years</td></tr>
<tr><td>Key Findings</td><td>Two new specifications have been established as the only valid methods for measuring PPO and other processed CMJ variables when using a force platform for measuring human performance in children aged 7 to 11 years</td></tr>
<tr><td colspan="2">Chapter 7: Experimental Study 4: The Development of Regression Equations to Estimate Peak Mechanical Power Output in Children Aged 7 to 11 Years</td></tr>
<tr><td>Objective</td><td>To use regression analysis to estimate of lower body peak mechanical power output in children aged 7 to 11 years</td></tr>
<tr><td>Key Findings</td><td>Body mass was found to have the highest correlation with actual PPO ($r = 0.821$) and flight height ($r = 0.226$). The regression models demonstrated large positive correlations with the actual PPO value with Pearson r values of 0.781-0.91. The regression models predicted 61% - 84% of the variance in actual PPO, with an associated standard estimate of error all regression models ranging from 9.6-15.1% of the mean (102-177 W)</td></tr>
</table>

Chapter 8 Synthesis of Research Findings

8.1 Synthesis of Research Findings

The aim of this thesis was to develop a criterion method for assessing countermovement jump variables in children aged 7 to 11 years. This thesis also sought to develop prediction equations for estimating PPO in the field once the criterion method for assessing countermove jump variables was developed. The aim of this thesis was achieve through a series of research objectives and questions that formed four experimental studies, as outlined in the introduction and summarised within the thesis map.

This thesis incorporated several analytical techniques such as allometric modelling, event identification signal processing and multiple regression modelling which have enabled significant advances in our understanding of measuring CMJ neuromuscular performance in children. Specifically, using these techniques, this thesis addresses, i) the differences between children aged 7 to 11 years and elite adults CMJ force time history data; ii) the effect of body size on CMJ variables and how to interpret apparent age related differences, iii) the development of an criterion, method specification for measuring processed CMJ force-time (F/T) history variables in children aged 7 to 11 years, iv) the use of regression equations to estimate PPO in children aged 7 to 11 years.

Experimental Chapter 1 sought to understand the differences in absolute force time history variables between children aged 7 to 11 years and elite adults, and established whether a new criterion method should be developed for children aged 7 to 11 years. This work established that there are significant differences in absolute F/T history variables, bodyweight (BW), peak force (Fmax), in-jump minimum force (IMF), in-jump force range (IFR) and basic force development (BRFD). It has shown that elite adults have significantly different and considerably higher, values for all variables ($p < 0.05$). The results of the chapter suggest that the current elite adult criterion method (EACM) for deriving processed CMJ F/T history variables, such as peak mechanical power output (PPO), impulse, and jump height, may be over-specified for children aged 7 to 11 years. This is an important consideration given the cost of hardware needed to sample data to the adult specification of 16 bits at 1000 Hz. Consequently, if an age specific criterion method (an established standard protocol for measuring processed CMJ variables via a force platform in children) was developed, and indicated the measurement of CMJ performance can be attained from lower specifications than the current EACM. This would result in greater availability to test neuromuscular performance in children due to a lower manufacturing cost of the equipment. Furthermore, the chapter demonstrated that the majority of the body of literature that reported processed F/T history variables in children should be interpreted with caution due to non-standardised methods used to derive processed CMJ variables, in addition, to the interchangeable use of unprocessed and scaled values to report CMJ results. This chapter was the first to present description of unprocessed and processed CMJ variables, in addition to characterising the differences of absolute unprocessed CMJ variables in children aged 7 to 11 years and elite adults, in addition, to identifying the direction of the following chapters which was to i) investigate the effect of body size on unprocessed CMJ variables in children aged 7 to 11 years and ii) to develop a new criterion method for deriving processed CMJ variables in children aged 7 to 11 years.

Prior to the determination of a new criterion method for children, the effect of body size on children was investigated in order to further understand the conflicting evidence presented within the literature about the effect of age and sex on child CMJ performance, whilst also identifying whether more than one criterion method was needed to be developed for children aged 7 to 11 years. Consequently, this chapter was the first study to provide a comparison of unprocessed absolute, normalised and allometric scaled CMJ variables in children aged 7 to 11 years. The key findings from the study highlighted that there was no significant sex differences for any absolute, normalised and allometrically scaled CMJ variables. This confirmed previous research and enables the pooling of boys and girls for group comparisons. Body size was found to have a significant effect on unprocessed CMJ variables, with no significant age differences observed for normalised or allometric scaled values whereas, significant differences where observed for absolute variables BW, IMF, Fmax and IFR between school year 3 and 4 when compared to school years 5 and 6. This suggests that if CMJ variables are scaled children can be represented as one homogenous group whereas, if absolute CMJ variables are used, further groups are required. This has significant implications for the determination of processed CMJ variables and demonstrates more than one criterion method is needed to be developed in order to determine processed CMJ variables in children aged 7 to 11 years. This study provided empirical evidence that analytical techniques such as normalising and allometrically scaling data, significantly alters the interpretation of CMJ data. The use of both absolute and scaled CMJ variables must therefore be incorporated into future studies to identify whether changes in CMJ performance occur as a result of an intervention *per se* rather than just the natural increases in body size associated with age.

Whilst the benefit of measuring processed CMJ variables in children has become apparent within the literature. *Experimental Chapter 1* and *Experimental Chapter 2* utilised unprocessed CMJ F/T history variables as no criterion method existed for measuring processed CMJ F/T history variables in children. As a result, no processed CMJ variables can measured in children as the results would be unclear. The use of unprocessed CMJ allowed valid initial investigations into CMJ performance in children, highlighting significant differences between child and elite adult CMJ data, in addition, to differences occurring between children. The results of these findings demonstrated that children are not mini-adults and require a population specific protocol for measuring processed CMJ variables, with the findings of the second study highlighting that the development of more than one criterion method for measuring processed CMJ variables was required. Therefore, the aim of *Experimental Chapter 3* was the determination of specifications for measuring lower body instantaneous peak mechanical power output (PPO) (a key processed variable in neuromuscular assessment) from a CMJ in children aged 7 to 11 years.

Experimental Chapter 3 utilised signal processing techniques, such as event identification, in order to develop two new specifications for establishing a valid criterion method for measuring PPO and other processed CMJ F/T history variables in children aged 7 to 11 years. Consequently, this also enabled the valid measurement of other processed CMJ variables, such as impulse, velocity, jump height and rate of force development, as a number of specifications quantified within the study are essential for deriving these other processed CMJ variables. The differences demonstrated between the two new criterion methods for children aged 7 to 11 and the EACM will facilitate the use of cheaper equipment, subsequently offering greater availability and application of the accurate assessment of neuromuscular performance in children aged

7 to 11 years. The establishment of the two criterion methods provides a foundation for all future and reapplication of past studies that look to investigate processed CMJ variables in children and their association with health and performance factors, for example changes observed in jump height and its association with growth and maturation, or the use of PPO to help identify children at risk of motor disorders in primary school or National Health Service screenings.

Experimental Chapter 4 sought to augment the findings of *Experimental Chapter 3* by using regression analysis to estimate PPO in children aged 7 to 11 years, as no method existed for children. As a result in adult regression were being used as some researchers and practitioners did not having accesses to the force platform criterion method. A cheaper alternative to the lab-based methods previously described were developed using easily measured variables in the field such as body mass and flight. The regression models that were developed are valid for the measurement of estimating PPO for group means in children aged 7 to 11 years with an associated standard estimate of error all regression models ranging from 9.6 - 15.1% of the mean.

8.2 Thesis Limitations

Two considerations for measuring neuromuscular performance in children were highlighted in *Experimental Chapters 2 and 4*. The first consideration was the frequency for collecting neuromuscular performance variables in children to represent a school year group as a potential limitation of *Experimental Chapter 2* is the use of one time point taken from the middle of the school year to represent the school year group. Indeed, whilst parametric assumptions of normality and homogeneity of variances were maintained for each group by taking randomised samples from a larger pool of data, the current method of assessing children by one time point in the school year may not be the best representation of neuromuscular performance of that school year group, as the youngest and oldest possible ages are not measured. Previous research has suggested 3-month intervals for the frequency of assessment for longitudinal tracking of maturation status as it enables worthwhile changes in growth to take place. Nonetheless, the applicability of this to CMJ variables remains to be elucidated. The second consideration was how to best represent age in children, for example, by school year, chronological age or maturation status. The concluding factors highlighted that primary school children should be represented by school year rather than chronological age or maturation status due to the engagement of formal physical literacy and extracurricular physical activities which fall in line with the child's school year. If chronological age or maturation status was chosen this could potentially affect the neuromuscular performance results reported, as the children could be selected from a variety of year groups. For example, if chronological age was chosen to determine groups, a child born on the 31st of August and a child born on the 1st of September could be placed within the same group as the children are only separated by one day. However, this method of grouping children will demonstrate favouritism towards the older child, as the older child has undertaken an extra year of formal physical literacy and extracurricular physical activities than the younger child.

8.3 Directions for Future Research

Overall, this thesis was able to achieve the thesis aim and research objectives and questions, successfully characterising and developing methods to assess or estimate neuromuscular performance variables in children aged 7 to 11 years through techniques, such as allometric modelling, event identification signal processing, and multiple regression modelling. This thesis has expanded the current evidence base on the assessment of neuromuscular performance in children by providing develop criterion methods for assessing processed variables in children aged 7 to 11 year and using regression equations to estimate PPO in children aged 7 to 11 years.. Future research should seek to employ the developed criterion methods for children aged 7 to 11 years described in this thesis for the determination of normative data, the characterisation of processed CMJ variables in children against other populations and the potential use of unprocessed and processed CMJ variables to help identify motor diseases and talent identification in children. Additionally, the developed regression equations for estimating PPO should be utilised for the estimation of group mean neuromuscular performance in children and compared to currently, employed adult regression equations for estimating PPO in children to further valid its use against a neutral data set. Furthermore, a body of work similar to this thesis should be produced in order to characterise the differences in adolescents, children and adults in order to determine whether an age specific criterion method is required for the measurement of adolescent CMJ processed F/T history variables, as no criterion method currently exists. Finally, a number of questions and considerations have been highlighted for future research measuring neuromuscular performance in children: i) how data is manipulated and reported, ii) how best to represent the age of the child and iii) and what is the optimum frequency to collect neuromuscular performance data in children.

Chapter 9 References

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology*, *93*(4), 1318–1326. http://doi.org/10.1152/japplphysiol.00283.2002

Abernethy, P., Wilson, G., & Logan, P. (1995). Strength and Power Assessment. *Sports Medicine*, *19*(6), 401–417. http://doi.org/10.2165/00007256-199519060-00004

Amonette, W. E., Brown, L. E., De Witt, J. K., Dupler, T. L., Tran, T. T., Tufano, J. J., & Spiering, B. A. (2012). Peak Vertical Jump Power Estimations in Youths and Young Adults. *Journal of Strength and Conditioning Research*, *26*(7), 1749–1755. http://doi.org/10.1519/JSC.0b013e3182576f1e

Andersen, L. L., & Aagaard, P. (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology*, *96*(1), 46–52. http://doi.org/10.1007/s00421-005-0070-z

Angelozzi, M., Madama, M., Corsica, C., Calvisi, V., Properzi, G., McCaw, S. T., & Cacchio, A. (2012). Rate of Force Development as an Adjunctive Outcome Measure for Return-to-Sport Decisions After Anterior Cruciate Ligament Reconstruction. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(9), 772–780. http://doi.org/10.2519/jospt.2012.3780

Atkinson, G., & Nevill, A. M. (1998). Statistical Methods For Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine*, *26*(4), 217–238. http://doi.org/10.2165/00007256-199826040-00002

Bagheri, J., van den Berg-Emons, R. J., Pel, J. J., Horemans, H. L., & Stam, H. J. (2011). Acute Effects of Whole-Body Vibration on Jump Force and Jump Rate of Force Development: A Comparative Study of Different Devices. *Journal of Strength and Conditioning Research*, *26*(3), 1. http://doi.org/10.1519/JSC.0b013e31822a5d27

Balsalobre-Fernández, C., Glaister, M., & Lockey, R. A. (2015). The validity and reliability of an iPhone app for measuring vertical jump performance. *Journal of Sports Sciences*, *33*(15), 1574–1579. http://doi.org/10.1080/02640414.2014.996184

Balsalobre-Fernández, C., Tejero-González, C. M., del Campo-Vecino, J., & Bavaresco, N.

(2014). The Concurrent Validity and Reliability of a Low-Cost, High-Speed Camera-Based Method for Measuring the Flight Time of Vertical Jumps. *Journal of Strength and Conditioning Research*, *28*(2), 528–533. http://doi.org/10.1519/JSC.0b013e318299a52e

Bartlett, R. (1997). *Introduction to Sports Biomechanics. Analyzing Human Movement Patterns* (2nd ed.). Routledge. http://doi.org/10.4324/9780203476161

Bassa, E., Kotzamanidis, C., Patikas, D., & Paraschos, I. (2001). The effect of age on isokinetic concentric and eccentric moment of knee extensors. *Isokinetics and Exercise Science*, *9*(4), 155–161.

Batterham, A. M., & George, K. P. (1997). Allometric modeling does not determine a dimensionless power function ratio for maximal muscular function. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *83*(6), 2158–66.

Baumgartner, T. a., & Chung, H. (2001). Confidence Limits for Intraclass Reliability Coefficients. *Measurement in Physical Education and Exercise Science*, *5*(3), 179–188. http://doi.org/10.1207/S15327841MPEE0503_4

Bellumori, M., Jaric, S., & Knight, C. A. (2011). The rate of force development scaling factor (RFD-SF): Protocol, reliability, and muscle comparisons. *Experimental Brain Research*, *212*(3), 359–369. http://doi.org/10.1007/s00221-011-2735-7

Beunen, G. P. (1988). *Adolescent Growth and Motor Performance: A Longitudinal Study of Belgian Boys. 1988*. Human Kinetics.

Beunen, G. P., & Malina, R. M. (2008). Growth and biologic maturation: Relevance to athletic performance. In H. Hebestreit & O. Bar-Or (Eds.), *The Young Athlete* (pp. 3–17). Oxford, UK: Blackwell Publishing Ltd. http://doi.org/10.1002/9780470696255.ch1

Bevan, H. R., Owen, N. J., Cunningham, D. J., Kingsley, M. I. C., & Kilduff, L. P. (2009). Complex training in professional rugby players: influence of recovery time on upper-body power output. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *23*(6), 1780–1785. http://doi.org/10.1519/JSC.0b013e3181b3f269

Bitar, A., Vernet, J., Coudert, J., & Vermorel, M. (2000). Longitudinal changes in body composition, physical capacities and energy expenditure in boys and girls during the onset of puberty. *European Journal of Nutrition*, *39*(4), 157–163. http://doi.org/10.1007/s003940070019

Bland, M. J., & Altman, D. G. (1986). Statistical Methods for Assessing Agreement Between Two Methods of Clinical Measurement. *The Lancet*, *327*(8476), 307–310. http://doi.org/10.1016/S0140-6736(86)90837-8

Blattner, S. E., & Noble, L. (1979). Relative effects of isokinetic and plyometric training on vertical jumping performance. *Research Quarterly. American Alliance for Health, Physical Education, Recreation and Dance*, *50*(4), 583–588.

Bobbert, M. F., & Casius, L. J. R. (2005). Is the effect of a countermovement on jump height due to active state development? *Medicine and Science in Sports and Exercise*, *37*(3), 440–446. http://doi.org/10.1249/01.MSS.0000155389.34538.97

Bobbert, M. F., & van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal of Biomechanics*, *21*(3), 249–262. http://doi.org/10.1016/0021-9290(88)90175-3

Borms, J. (1986). The child and exercise: An overview. *Journal of Sports Sciences*, *4*(1), 3–20. http://doi.org/10.1080/02640418608732093

Bosco, C., Luhtanen, P., & Komi, P. V. (1983). A simple method for measurement of mechanical power in jumping. *European Journal of Applied Physiology and Occupational Physiology*, *50*(2), 273–282. http://doi.org/10.1007/BF00422166

Bovet, P., Auguste, R., & Burdette, H. (2007). Strong inverse association between physical fitness and overweight in adolescents: a large school-based survey. *International Journal of Behavioral Nutrition and Physical Activity*, *4*(1), 24. http://doi.org/10.1186/1479-5868-4-24

Branta, C., Haubenstricker, J., & Seefeldt, V. (1984). Age changes in motor skills during childhood and adolescence. *Exercise and Sport Sciences Reviews*, *12*, 467–520.

Buckthorpe, M., Morris, J., & Folland, J. P. (2012). Validity of vertical jump measurement devices. *Journal of Sports Sciences*, *30*(1), 63–69. http://doi.org/10.1080/02640414.2011.624539

Busche, P., Rawer, R., Rakhimi, N., Lang, I., & Martin, D. D. (2013). Mechanography in childhood: References for force and power in counter movement jumps and chair rising tests. *Journal of Musculoskeletal Neuronal Interactions*, *13*(2), 213–226.

Canavan, P. K., & Vescovi, J. D. (2004). Evaluation of power prediction equations: Peak vertical jumping power in women. *Medicine and Science in Sports and Exercise*, *36*(9), 1589–1593. http://doi.org/10.1249/01.MSS.0000139802.96395.AC

Cantell, M. H., Smyth, M. M., & Ahonen, T. P. (1994). Clumsiness in adolescence: Educational, motor, and social outcomes of motor delay detected at 5 years. *Adapted Physical Activity Quarterly, 11*(2), 115–129. http://doi.org/10.1123/apaq.11.2.115

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., … Stone, M. H. (2004). The Relationship Between Vertical Jump Power Estimates and Weightlifting Ability: A Field-Test Approach. *The Journal of Strength and Conditioning Research, 18*(3), 534. http://doi.org/10.1519/R-13213.1

Cavagna, G. A. (1975). Force platforms as ergometers. *Journal of Applied Physiology*, *39*(1), 174–9. http://doi.org/10.1093/icb/40.1.101

Chatzinikolaou, A., Fatouros, I. G., Gourgoulis, V., Avloniti, A., Jamurtas, A. Z., Nikolaidis, M. G., … Taxildaris, K. (2010). Time course of changes in performance and inflammatory responses after acute plyometric exercise. *Journal of Strength and Conditioning Research*, *24*(5), 1389–1398. http://doi.org/10.1519/JSC.0b013e3181d1d318

Cherif, M., Said, M., Chaatani, S., Nejlaoui, O., Gomri, D., & Abdallah, A. (2012). The effect of a combined high-intensity plyometric and speed training program on the running and jumping ability of male handball players. *Asian Journal of Sports Medicine*, *3*(1), 21–28. http://doi.org/10.1519/R-14944.1

Clark, J., Phillips, S., & R, P. (1989). Developmental stability in jumping. *Developmental Psychology*, (25), 929–935.

Cleather, D. J. (2006). Adjusting Powerlifting Performances for Differences in Body Mass. *The Journal of Strength and Conditioning Research*, *20*(2), 412. http://doi.org/10.1519/R-17545.1

Clutch, D., Wilton, M., McGown, C., & Bryce, G. R. (1983). The effect of depth jumps and weight training on leg strength and vertical jump. *Research Quarterly for Exercise and Sport*, *54*(1), 5–10. http://doi.org/10.1080/02701367.1983.10605265

Cohen, J. (1973). Eta-Squared and Partial Eta-Squared in Fixed Factor Anova Designs. *Educational and Psychological Measurement*, *33*(1), 107–112. http://doi.org/10.1177/001316447303300111

Cook, C. J., Kilduff, L. P., Crewther, B. T., Beaven, M., & West, D. J. (2014). Morning based strength training improves afternoon physical performance in rugby union players. *Journal of Science and Medicine in Sport*, *17*(3), 317–321. http://doi.org/10.1016/j.jsams.2013.04.016

Cormack, S. J. (2008). Neuromuscular fatigue and endocrine responses in elite Australian Rules. *International Journal of Sports Physiology and Performance*, *3*(March), 1–132.

Cormack, S. J., Newton, R. U., McGulgan, M. R., & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*, *3*(2), 131–144. http://doi.org/10.1123/ijspp.3.2.131

Cormie, P., McBride, J. M., & McCaulley, G. O. (2007). Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics*, *23*(2), 103–118. http://doi.org/10.1123/jab.23.2.103

Cormie, P., McCaulley, G. O., & McBride, J. M. (2007). Power Versus Strength-Power Jump Squat Training. *Medicine & Science in Sports & Exercise*, *39*(6), 996–1003. http://doi.org/10.1097/mss.0b013e3180408e0c

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise*, *42*(8), 1582–1598. http://doi.org/10.1249/MSS.0b013e3181d2013a

Crameri, R. M., Aagaard, P., Qvortrup, K., Langberg, H., Olesen, J., & Kjaer, M. (2007). Myofibre damage in human skeletal muscle: effects of electrical stimulation *versus* voluntary contraction. *The Journal of Physiology*, *583*(1), 365–380. http://doi.org/10.1113/jphysiol.2007.128827

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *19*(2), 349–357. http://doi.org/10.1519/14323.1

Cumming, S. P., Brown, D. J., Mitchell, S., Bunce, J., Hunt, D., Hedges, C., … Malina, R. M. (2017). Premier League academy soccer players' experiences of competing in a tournament bio-banded for biological maturation. *Journal of Sports Sciences*, 1–9. http://doi.org/10.1080/02640414.2017.1340656

Cumming, S. P., Lloyd, R. S., Oliver, J. L., Eisenmann, J. C., & Malina, R. M. (2017). Bio-banding in Sport: Applications to Competition, Talent Identification, and Strength and Conditioning of Youth Athletes. *Strength and Conditioning Journal*, *39*(2), 34–47.

http://doi.org/10.1519/SSC.0000000000000281

Cunningham, D. J., West, D. J., Owen, N. J., Shearer, D. A., Finn, C. V., Bracken, R. M., … Kilduff, L. P. (2013). Strength and power predictors of sprinting performance in professional rugby players. *Journal of Sports Medicine and Physical Fitness*, *53*(2), 105–111.

Dapena, J., & Chung, C. S. (1988). Vertical and radial motions of the body during the take-off phase of high jumping. *Medicine and Science in Sports and Exercise*, *20*(3), 290–302. http://doi.org/10.1016/0021-9290(87)90183-7

Davies, C. T. M., & Rennie, R. (1968). Human power output. *Nature*, *217*(5130), 770–771. http://doi.org/10.1038/217770a0

de Salles, P., Vasconcellos, F., de Salles, G., Fonseca, R., & Dantas, E. (2012). Validity and Reproducibility of the Sargent Jump Test in the Assessment of Explosive Strength in Soccer Players. *Journal of Human Kinetics*, *33*(1), 115–121. http://doi.org/10.2478/v10078-012-0050-4

Duncan, M. J., Hankey, J., Lyons, M., James, R. S., & Nevill, A. M. (2013). Peak Power Prediction In Junior Basketballers: Comparing Linear and Allometric Models. *Journal of Strength & Conditioning Research*, *27*(3), 597–603.

Duncan, M. J., Hankey, J., & Nevill, A. M. (2013). Peak-power estimation equations in 12- to 16-year old children: comparing linear with allometric models. *Pediatric Exercise Science*, *25*(19), 385–93.

Eagles, A. N., Sayers, M. G. L., Bousson, M., & Lovell, D. I. (2015). Current Methodologies and Implications of Phase Identification of the Vertical Jump: A Systematic Review and Meta-analysis. *Sports Medicine*, *45*(9), 1311–1323. http://doi.org/10.1007/s40279-015-0350-7

Feltner, M. E., Fraschetti, D. J., & Crisp, R. J. (1999). Upper extremity augmentation of lower extremity kinetics during countermovement vertical jumps. *Journal of Sports Sciences*, *17*(6), 449–466. http://doi.org/10.1080/026404199365768

Focke, A., Strutzenberger, G., Jekauc, D., Worth, A., Woll, A., & Schwameder, H. (2013). Effects of age, sex and activity level on counter-movement jump performance in children and adolescents. *European Journal of Sport Science*, *13*(5), 518–526. http://doi.org/10.1080/17461391.2012.756069

Ford, P., De Ste Croix, M., Lloyd, R., Meyers, R., Moosavi, M., Oliver, J., … Williams, C. (2011). The Long-Term Athlete Development model: Physiological evidence and application. *Journal of Sports Sciences*, *29*(4), 389–402. http://doi.org/10.1080/02640414.2010.536849

Fowler, A. (2012). *The Reliability of Peak Power Output in a Countermovement Jump in Children Aged 9 to 11 Years. Unpublished Dissertation.* Swansea University, UK.

Fricke, O., Stabrey, A., Tutlewski, B., & Schoenau, E. (2009). Mechanographic Analyses in Pediatrics: Allometric Scaling of 'Peak Jump Force' and Its Relationship to 'Maximal Isometric Grip Force' in Childhood and Adolescence. *Klinische Pädiatrie*, *221*(07), 436–439. http://doi.org/10.1055/s-0029-1238315

Fricke, O., Weidler, J., Tutlewski, B., & Schoenau, E. (2006). Mechanography - A new device for the assessment of muscle function in pediatrics. *Pediatric Research*, *59*(1), 46–49. http://doi.org/10.1203/01.pdr.0000191580.07644.1c

Gabbett, T. J. (2009). Physiological and anthropometric characteristics of starters and non-starters in junior rugby league players, aged 13-17 years. *Journal of Sports Medicine and Physical Fitness*, *49*(3), 233–239.

Gabel, L., Macdonald, H. M., Nettlefold, L., Race, D., & McKay, H. A. (2016). Reference data for jumping mechanography in Canadian children, adolescents and young adults. *Journal of Musculoskeletal & Neuronal Interactions*, *16*(4), 283–295.

Garnacho-Castaño, M. V., López-Lastra, S., & Maté-Muñoz, J. L. (2014). Reliability and validity assessment of a linear position transducer. *Journal of Sports Science and Medicine*, *14*(1), 128–136.

Genuario, S. E., & Dolgener, F. A. (1980). The relationship of isokinetic torque at two speeds to the vertical jump. *Research Quarterly for Exercise and Sport*, *51*(4), 593–598. http://doi.org/10.1080/02701367.1980.10609319

Gerodimos, V., Zafeiridis, A., Perkos, S., Dipla, K., Manou, V., & Kellis, S. (2008). The Contribution of Stretch-Shortening Cycle and Arm-Swing to Vertical Jumping Performance in Children, Adolescents, and Adult Basketball Players. *Pediatric Exercise Science*, *20*(4), 379–389. http://doi.org/10.1123/pes.20.4.379

Gissis, I., Papadopoulos, C., Kalapotharakos, V., Sotiropoulos, A., Komsis, G., & Manolopoulos, E. (2006). Strength and Speed Characteristics of Elite, Subelite, and Recreational Young Soccer Players. *Research in Sports Medicine*, *14*(3), 205–214.

http://doi.org/10.1080/15438620600854769

Glencross, D. J. (1966). The nature of the vertical jump test and the standing broad jump. *Research Quarterly of the American Association for Health, Physical Education and Recreation*, *37*(3), 353–359. http://doi.org/10.1080/10671188.1966.10614761

Gonzalez-Badillo, J. J., & Marques, M. C. (2010). Relationship between kinematic factors and countermovement jump height in trained track and field athletes. *J Strength Cond Res*, *24*(12), 3443–3447. http://doi.org/10.1519/JSC.0b013e3181bac37d

Gray, R. K., Start, K. B., & Glencross, D. J. (1962). A test of leg power. *Research Quarterly of the American Association for Health, Physical Education and Recreation*, *33*(1), 44–50. http://doi.org/10.1080/10671188.1962.10762085

Hanson, E. D., Leigh, S., Mynark, R. G., Hanson S Leigh, A. E., & Mynark, R. (2007). Acute effects of heavy- and light-load squat exercise on the kinetic measures of vertical jumping. *Journal of Strength and Conditioning Research*, *21*(4), 1012–1017. http://doi.org/10.1519/R-20716.1

Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1991). The effects of arms and countermovement on vertical jumping. *National Strength & Conditioning Association Journal*, *13*(3), 38. http://doi.org/10.1519/0744-0049(1991)013<0038:TEOAAC>2.3.CO;2

Harman, E. A., Rosenstein, M. T., Frykman, P. N., Rosenstein, R. M., & Kraemer, W. J. (1991). Estimation of Human Power Output from Vertical Jump. *Journal of Applied Sport Science Research*, *5*(5), 116–120.

Harrison, A. J., & Gaffney, S. (2001). Motor development and gender effects on stretch-shortening cycle performance. *Journal of Science and Medicine in Sport*, *4*(4), 406–15.

Hatze, H. (1998). Validity and Reliability of Methods for Testing Vertical Jumping Performance. *Journal of Applied Biomechanics*, *14*(2), 127–140. http://doi.org/10.1123/jab.14.2.127

Haubenstricker, J., & Seefeldt, V. (1986). Acquisition of motor skills during childhood. *Physical Activity and Well-Being*, 41–102.

Hay, J. A. (1992). Adequacy in and predilection for physical activity in children. *Clinical Journal of Sport Medicine*, *2*(3), 192–201. http://doi.org/10.1097/00042752-199207000-00007

Hertogh, C., & Hue, O. (2002). Jump evaluation of elite volleyball players using two methods: Jump power equations and force platform. *Journal of Sports Medicine and Physical Fitness*, *42*(3), 300–303.

Hoffman, J. R., Maresh, C. M., Newton, R. U., Rubin, M. R., French, D. N., Volek, J. S., … Kraemer, W. J. (2002). Performance, biochemical, and endocrine changes during a competitive football game. *Medicine and Science in Sports and Exercise*, *34*(11), 1845–1853. http://doi.org/10.1097/00005768-200211000-00023

Hoffman, J. R., Nusse, V., & Kang, J. (2003). The effect of an intercollegiate soccer game on maximal power performance. *Canadian Journal of Applied Physiology = Revue Canadienne de Physiologie Appliquee*, *28*(6), 807–817. http://doi.org/10.1139/h03-060

Hogan, J. (1991). Structure of physical performance in occupational tasks. *Journal of Applied Psychology*, *76*(4), 495–507. http://doi.org/10.1037/0021-9010.76.4.495

Holsti, L., Grunau, R. V. E., & Whitfield, M. F. (2002). Developmental coordination disorder in extremely low birth weight children at nine years. *Journal of Developmental and Behavioral Pediatrics : JDBP*, *23*(1), 9–15. http://doi.org/10.1097/00004703-200202000-00002

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R., & Nosaka, K. (2007). Comparison of Four Different Methods to Measure Power Output During the Hang Power Clean and the Weighted Jump Squat. *The Journal of Strength and Conditioning Research*, *21*(2), 314. http://doi.org/10.1519/R-22896.1

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J., & Nosaka, K. (2009). Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *Journal of Strength and Conditioning Research*, *23*(3), 874–82. http://doi.org/10.1519/JSC.0b013e3181a00ca2

Hori, N., Nosaka, K., McGuigan, M. R., & Newton, R. U. (2006). Comparison of Different Methods of Determining Power Output in Weightlifting Exercises. *Journal of Strength & Conditioning Research*, *28*(2), 34–40. http://doi.org/10.1519/1533-4295(2006)028

Isaacs, L. D. (1998). Comparison of the Vertec and Just Jump Systems for Measuring Height of Vertical Jump by Young Children. *Perceptual and Motor Skills*, *86*(2), 659–663. http://doi.org/10.2466/pms.1998.86.2.659

Jakobsen, M. D., Sundstrup, E., Randers, M. B., Kjær, M., Andersen, L. L., Krustrup, P., &

Aagaard, P. (2012). The effect of strength training, recreational soccer and running exercise on stretch-shortening cycle muscle performance during countermovement jumping. *Human Movement Science*, *31*(4), 970–986. http://doi.org/10.1016/j.humov.2011.10.001

Jaric, S. (2002). Muscle Strength Testing. *Sports Medicine*, *32*(10), 615–631. http://doi.org/10.2165/00007256-200232100-00002

Jaric, S., Mirkov, D., & Markovic, G. (2005). Normalizing physical performance tests for body size: a proposal for standardization. *Journal of Strength and Conditioning Research*, *19*(2), 467–474. http://doi.org/10.1519/R-15064.1

Jenkins, N. D. M., Housh, T. J., Traylor, D. A., Cochrane, K. C., Bergstrom, H. C., Lewis, R. W., … Cramer, J. T. (2014). The rate of torque development: A unique, non-invasive indicator of eccentric-induced muscle damage? *International Journal of Sports Medicine*, *35*(14), 1190–1195. http://doi.org/10.1055/s-0034-1375696

Jensen, J. L., Phillips, S. J., & Clark, J. E. (1994). For Young Jumpers, Differences are in the Movement's Control, Not its Coordination. *Research Quarterly for Exercise and Sport*, *65*(3), 258–268. http://doi.org/10.1080/02701367.1994.10607627

Johnson, B. L., & Nelson, J. K. (1979). Practical Measurements for Evaluation in Physical Education. Burgess Publishing Company, 426 South Sixth Street, Minneapolis, Minn.

Johnson, D. L., & Bahamonde, R. (1996). Power output estimate in university athletes. *Journal of Strength & Conditioning Research*, *10*(3), 161–166. http://doi.org/10.1519/1533-4287(1996)010<0161:POEIUA>2.3.CO;2

Jones, C. M. (2012). *The Reliability of Peak Power Output in a Countermovement Jump in Children Aged 7 to 9 Years. Unpublished Dissertation.* Swansea University, UK.

Kawamori, N., Crum, A. J., Blumert, P. A., Kulik, J. R., Childers, J. T., Wood, J. A., … Haff, G. G. (2005). Influence of Different Relative Intensities on Power Output During the Hang Power Clean: Identification of the Optimal Load. *The Journal of Strength and Conditioning Research*, *19*(3), 698. http://doi.org/10.1519/16044.1

Kibele, A. (1998). Possibilities and Limitations in the Biomechanical Analysis of Countermovement Jumps: A Methodological Study. *Journal of Applied Biomechanics*, *14*(1), 105–117. http://doi.org/10.1123/jab.14.1.105

Kilduff, L. P., Bevan, H. R., Owen, N., I.C. Kingsley, M., Bunce, P., Bennett, M. A., &

Cunningham, D. (2007). Optimal Loading for Peak Power Output during the Hang Power Clean in Professional Rugby Players. *International Journal of Sports Physiology and Performance*, *2*(3), 260–269. http://doi.org/10.1123/ijspp.2.3.260

Kirby, A., Sugden, D., & Purcell, C. (2014). Diagnosing developmental coordination disorders. *Archives of Disease in Childhood*, *99*(3), 292–296. http://doi.org/10.1136/archdischild-2012-303569

Knudson, D. V. (2009). Correcting the use of the term "power" in the strength and conditioning literature. *Journal of Strength & Conditioning Research*, *23*(6), 1902–8. http://doi.org/10.1519/JSC.0b013e3181b7f5e5

Komi, P. V. (1992). Strength and power in sport - Stretch–Shortening Cycle. *The Encyclopaedia of Sports Medicine*, *III*(11), 184–202.

Korff, T., Horne, S. L., Cullen, S. J., & Blazevich, A. J. (2009). Development of lower limb stiffness and its contribution to maximum vertical jumping power during adolescence. *The Journal of Experimental Biology*, *212*(Pt 22), 3737–3742. http://doi.org/10.1242/jeb.033191

Lake, J. P., Lauder, M. A., & Smith, N. A. (2012). Barbell Kinematics Should Not Be Used to Estimate Power Output Applied to the Barbell-and-Body System Center of Mass During Lower-Body Resistance Exercise. *Journal of Strength and Conditioning Research*, *26*(5), 1302–1307. http://doi.org/10.1519/JSC.0b013e31822e7b48

Lang, I., Busche, P., Rakhimi, N., Rawer, R., & Martin, D. D. (2013). Mechanography in childhood: References for grip force, multiple one-leg hopping force and whole body stiffness. *Journal of Musculoskeletal Neuronal Interactions*, *13*(2), 227–235.

Lara, A. J., Abián, J., Alegre, L. M., Jiménez, L., & Aguado, X. (2006). Assessment of power output in jump tests for applicants to a sports sciences degree. *Journal of Sports Medicine and Physical Fitness*, *46*(3), 419–424.

Lees, A., Graham-Smith, P., & Flower, N. (1994). A Biomechanical Analysis of the Last Stride,Touchdown,and Takeoff Characteristics of the Men's Long Jump.PDF. *Journal of Applied Biomechanics*, *10*(1), 61–78. http://doi.org/10.1123/jab.10.1.61

Lees, A., Vanrenterghem, J., & Clercq, D. D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics*, *37*(12), 1929–1940. http://doi.org/10.1016/j.jbiomech.2004.02.021

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). The maximal and submaximal vertical jump: implications for strength and conditioning. *Journal of Strength & Conditioning Research*, *18*(4), 787–91. http://doi.org/10.1519/14093.1

Levene, H. (1960). Robust tests for equality of variances. *Contributions to Probability and Statistics, Essays in Honor of Harold Hotelling*, 279–292.

Li, L., Olson, M. W., & Winchester, J. B. (2008). A Proposed Method for Determining Peak Power in the Jump Squat Exercise. *Journal of Strength and Conditioning Research*, *22*(2), 326–331. http://doi.org/10.1519/JSC.0b013e3181635606

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physiology*, *69*(11), 1198–1204. http://doi.org/10.1119/1.1397460

Lloyd, R. S., & Oliver, J. L. (2013). *Strength and Conditioning for Young Athletes : Science and application.* Taylor and Francis.

Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Myer, G. D., & De Ste Croix, M. B. A. (2014). Chronological Age vs. Biological Maturation. *Journal of Strength and Conditioning Research*, *28*(5), 1454–1464. http://doi.org/10.1519/JSC.0000000000000391

Lloyd, R. S., Oliver, J. L., Radnor, J. M., Rhodes, B. C., Faigenbaum, A. D., & Myer, G. D. (2015). Relationships between functional movement screen scores, maturation and physical performance in young soccer players. *Journal of Sports Sciences*, *33*(1), 11–19. http://doi.org/10.1080/02640414.2014.918642

Lohmann, T., Roche, A., & Martorell, R. (1988). *Anthropometric Standardization Reference Manual*. Champaign, IL: Human Kinetics.

Losse, A., Henderson, S. E., Elliman, D., Hall, D., Knight, E., & Jongmans, M. (1991). Clumsiness in Children-Do they Grow out Of It? A 10-Year Follow-Up Study. *Developmental Medicine & Child Neurology*, *33*(1), 55–68. http://doi.org/10.1111/j.1469-8749.1991.tb14785.x

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N. A., & Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. *European Journal of Applied Physiology, 116*(6), 1091–1116. http://doi.org/10.1007/s00421-016-3346-6

Magnúsdóttir, Á., Porgilsson, B., & Karlsson, B. (2014). Comparing three devices for jump height measurement in a heterogeneous group of subjects. *Journal of Strength and Conditioning Research*, *28*(10), 2837–2844. http://doi.org/10.1519/JSC.0000000000000464

Malina, R. M., Bouchard, C., & Bar-Or, O. (2005). *Growth, Maturation, and Physical Activity* (2nd ed., Vol. 9). Human Kinetics.

Markovic, G., & Jaric, S. (2004). Movement performance and body size: the relationship for different groups of tests. *European Journal of Applied Physiology*, *92*(1–2), 139–149. http://doi.org/10.1007/s00421-004-1076-7

Markovic, G., & Jaric, S. (2005). Scaling of muscle power to body size: The effect of stretch-shortening cycle. *European Journal of Applied Physiology*, *95*(1), 11–19. http://doi.org/10.1007/s00421-005-1385-5

Martin, R. J. F., Dore, E., Twisk, J., Van Praagh, E., Hautier, C. A., & Bedu, M. (2004). Longitudinal Changes of Maximal Short-Term Peak Power in Girls and Boys during Growth. *Medicine and Science in Sports and Exercise*, *36*(3), 498–503. http://doi.org/10.1249/01.MSS.0000117162.20314.6B

McGuigan, M. R., Cormack, S. J., & Gill, N. D. (2013). Strength and Power Profiling of Athletes: Selecting Tests and How to Use the Information for Program Design. *Strength and Conditioning Journal*, *0*(0), 1–8. http://doi.org/10.1097/SSC.0000000000000011

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). The Role of Rate of Force Development on Vertical Jump Performance. *Journal of Strength and Conditioning Research*, *25*(2), 379–385. http://doi.org/10.1519/JSC.0b013e3181be305c

Meylan, C. M. P., Cronin, J. B., Oliver, J. L., Hughes, M. G., & Manson, S. (2014). An Evidence-Based Model of Power Development in Youth Soccer. *International Journal of Sports Science & Coaching*, *9*(5), 1241–1264. http://doi.org/10.1260/1747-9541.9.5.1241

Mian Qaisar, S., Fesquet, L., & Renaudin, M. (2009). Adaptive rate sampling and filtering based on level crossing sampling. *Eurasip Journal on Advances in Signal Processing*, *2009*(1), 1–13. http://doi.org/10.1155/2009/971656

Moir, G. L., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *Journal of Strength and Conditioning Research / National Strength &*

Conditioning Association, *18*(2), 276–280. http://doi.org/10.1519/R-13093.1

Moir, G. L., Garcia, A., & Dwyer, G. B. (2009). Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology and Performance*, *4*(3), 317–330. http://doi.org/10.1249/01.mss.0000322822.91584.94

Moir, G. L., Sanders, R., Button, C., & Glaister, M. (2005). The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps. *Journal of Strength and Conditioning Research*, *19*(1), 140–145. http://doi.org/10.1519/14803.1

Mundy, P. D., Lake, J. P., Carden, P. J. C., Smith, N. A., & Lauder, M. A. (2016). Agreement between the force platform method and the combined method measurements of power output during the loaded countermovement jump. *Sports Biomechanics*, *15*(1), 23–35. http://doi.org/10.1080/14763141.2015.1123761

Mundy, P. D., Smith, N. A., Lauder, M. A., & Lake, J. P. (2016). The effects of barbell load on countermovement vertical jump power and net impulse. *Journal of Sports Sciences*, *00*(00), 1–7. http://doi.org/10.1080/02640414.2016.1236208

Neu, C. M., Rauch, F., Rittweger, J., Manz, F., & Schoenau, E. (2002). Influence of puberty on muscle development at the forearm. *American Journal of Physiology. Endocrinology and Metabolism*, *283*(1), E103–E107. http://doi.org/10.1152/ajpendo.00445.2001

Nevill, A. M., & Holder, R. L. (1995). Scaling, normalizing, and per ratio standards: an allometric modeling approach. *Journal of Applied Physiology*, *79*(3), 1027–31.

Nevill, A. M., Holder, R. L., Baxter-Jones, A., Round, J. M., & Jones, D. A. (1998). Modeling developmental changes in strength and aerobic power in children. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *84*(3), 963–70.

Newton, I. (1667). *Philosophiae Naturalis Principia Mathematica*.

Nibali, M. L., Tombleson, T., Brady, P. H., & Wagner, P. (2015). Influence of Familiarization and Competitive Level on the Reliability of Countermovement Vertical Jump Kinetic and Kinematic Variables. *Journal of Strength and Conditioning Research*, *29*(10), 2827–2835. http://doi.org/10.1519/JSC.0000000000000964

Nuzzo, J. L., Anning, J. H., & Scharfenberg, J. M. (2011). The Reliability of Three Devices

Used for Measuring Vertical Jump Height. *Journal of Strength and Conditioning Research*, *25*(9), 2580–2590. http://doi.org/10.1519/JSC.0b013e3181fee650

Nuzzo, J. L., McBride, J. M., Cormie, P., & Mccaulley, G. O. (2008). Relationship Between Countermovement Jump Performance and Multijoint Isometric And Dynamic Tests Of Strength. *Journal of Strength & Conditioning Research*, *22*(3), 699–707.

Nyquist, H. (1928). Certain Topics in Telegraph Transmission Theory. *Transactions of the American Institute of Electrical Engineers*, *47*(2), 617–644. http://doi.org/10.1109/T-AIEE.1928.5055024

O'brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. A., & Maganaris, C. N. (2010). Muscle-tendon structure and dimensions in adults and children. *Journal of Anatomy*, *216*(5), 631–642. http://doi.org/10.1111/j.1469-7580.2010.01218.x

Oliver, J., Armstrong, N., & Williams, C. (2008). Changes in jump performance and muscle activity following soccer-specific exercise. *Journal of Sports Sciences*, *26*(2), 141–148. http://doi.org/10.1080/02640410701352018

Owen, N. J. (2008). *Development of a field test to estimate peak vertical mechanical power of elite male rugby union players. Unpublished Master's Thesis.* Swansea University, UK.

Owen, N. J., Watkins, J., Kilduff, L. P., Bevan, H. R., & Bennett, M. A. (2014). Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump. *Journal of Strength and Conditioning Research*, *28*(6), 1552–1558. http://doi.org/10.1519/JSC.0000000000000311

Parker, D. F., Round, J. M., Sacco, P., & Jones, D. A. (1990). A Cross-sectional survey of upper and lower limb strength in boys and girls during childhood and adolescence. *Annals of Human Biology*, *17*(3), 199–211. http://doi.org/10.1080/03014469000000962

Payne, A. H., Slater, W. J., & Telford, T. (1968). The use of a force platform in the study of athletic activities. a preliminary investigation. *Ergonomics*, *11*(2), 123–143. http://doi.org/10.1080/00140136808930950

Place, N., Yamada, T., Bruton, J. D., & Westerblad, H. (2010). Muscle fatigue: From observations in humans to underlying mechanisms studied in intact single muscle fibres. *European Journal of Applied Physiology*, *110*(1), 1–15. http://doi.org/10.1007/s00421-010-1480-0

Pohlmann, K. C. (2010). *Principles of digital audio* (6th ed.). McGraw-Hill Companies Inc.

Quagliarella, L., Sasanelli, N., Belgiovine, G., Moretti, L., & Moretti, B. (2011). Power Output Estimation in Vertical Jump Performed by Young Male Soccer Players. *Journal of Strength and Conditioning Research*, *25*(6), 1638–1646. http://doi.org/10.1519/JSC.0b013e3181d85a99

Quatman, C. E. (2005). Maturation Leads to Gender Differences in Landing Force and Vertical Jump Performance: A Longitudinal Study. *American Journal of Sports Medicine*, *34*(5), 806–813. http://doi.org/10.1177/0363546505281916

Raffalt, P. C., Alkjær, T., & Simonsen, E. B. (2016a). Intra- and inter-subject variation in lower limb coordination during countermovement jumps in children and adults. *Human Movement Science*, *46*, 63–77. http://doi.org/10.1016/J.HUMOV.2015.12.004

Raffalt, P. C., Alkjær, T., & Simonsen, E. B. (2016b). Joint dynamics and intra-subject variability during countermovement jumps in children and adults. *Journal of Biomechanics*, *49*(13), 2968–2974. http://doi.org/10.1016/J.JBIOMECH.2016.07.010

Ramírez-Vélez, R., Correa-Bautista, J. E., Lobelo, F., Cadore, E. L., Alonso-Martinez, A. M., & Izquierdo, M. (2017). Vertical Jump and Leg Power Normative Data for Colombian Schoolchildren Aged 9–17.9 Years. *Journal of Strength and Conditioning Research*, *31*(4), 990–998. http://doi.org/10.1519/JSC.0000000000001550

Robertson, G., Caldwell, G., & Hamill, J. (2013). *Research Methods in Biomechanics, 2E*.

Sargent, L. W. (1924). Some observations on the Sargent test of neuromuscular efficiency. *American Physical Education Review*, *29*(44), 47–56.

Sawyer, D. T., Ostarello, J. Z., Suess, E. a, & Dempsey, M. (2002). Relationship between football playing ability and selected performance measures. *Journal of Strength and Conditioning Research*, *16*(4), 611–616. http://doi.org/10.1519/1533-4287(2002)016<0611:RBFPAA>2.0.CO;2

Sayers, S. P., Harackiewicz, D. V, Harman, E. A., Frykman, P. N., & Rosenstein, M. T. (1999). Cross-validation of three jump power equations. *Medicine and Science in Sports and Exercise*, *31*(4), 572–7. http://doi.org/10.1097/00005768-199904000-00013

Schoenau, E., & Fricke, O. (2008). Mechanical influences on bone development in children. *European Journal of Endocrinology*, *159*(1), S27-31. http://doi.org/10.1530/EJE-08-0312

Seger, J. Y., & Thorstensson, A. (2000). Muscle strength and electromyogram in boys and girls followed through puberty. *European Journal of Applied Physiology and Occupational Physiology*, *81*(1–2), 54–61. http://doi.org/10.1007/PL00013797

Sheppard, J. M., Cormack, S., Taylor, K.-L., McGuigan, M. R., & Newton, R. U. (2008). Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: the incremental load power profile. *Journal of Strength and Conditioning Research*, *22*(4), 1320–1326. http://doi.org/10.1519/JSC.0b013e31816d671b

Sheppard, J. M., Doyle, T. L., & Taylor, K.-L. (2008). A methodological and performance comparison of free weight and smith-machine jump squats. *Journal of Australian Strength and Conditioning*, (16), 5–9.

Shetty, A. B. (2002). Leg Power: Estimation of leg power: A two-variable model. *Sports Biomechanics*, *1*(2), 147–155. http://doi.org/10.1080/14763140208522793

Shetty, A. B., & Etnyre, B. R. (1989). Contribution of arm movement to the force components of a maximum vertical jump. *Journal Orthopaedic & Sports Physical Therapy*, *11*(5), 198–201. http://doi.org/10.2519/jospt.1989.11.5.198

Soriano, M. A., Jiménez-Reyes, P., Rhea, M. R., & Marín, P. J. (2015). The Optimal Load for Maximal Power Production During Lower-Body Resistance Exercises: A Meta-Analysis. *Sports Medicine*, *45*(8), 1191–1205. http://doi.org/10.1007/s40279-015-0341-8

Sparkes, W., Turner, A. ., Weston, M., Russell, M., Johnston, M. ., & Kilduff, L. . (2018). The neuromuscular, biochemical, endocrine and mood responses to small-sided games training in professional soccer. *Journal of Strength and Conditioning Research*, 1. http://doi.org/10.1519/JSC.0000000000002424

Stokes, M. (1985). Reliability and Repeatability of Methods for Measuring Muscle in Physiotherapy. *Physiotherapy Practice*, *1*(2), 71–76. http://doi.org/10.3109/09593988509163853

Stratton, G., & Oliver, J. (2013). The impact of growth and maturation on physical performance. In R. S. Lloyd & J. L. Oliver (Eds.), *Strength and Conditioning for Young Athletes: Science and Application* (pp. 3–18). R.

Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of error in determining countermovement jump height with the impulse method. *Journal* *of Applied Biomechanics*, *17*(1), 43–54. http://doi.org/10.1123/jab.17.1.43

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular Strength in Athletic Performance. *Sports Medicine*, *46*(10), 1419–1449. http://doi.org/10.1007/s40279-016-0486-0

Sumnik, Z., Matyskova, J., Hlavka, Z., Durdilova, L., Soucek, O., & Zemkova, D. (2013). Reference data for jumping mechanography in healthy children and adolescents aged 6-18 years. *Journal of Musculoskeletal & Neuronal Interactions*, *13*(3), 297–311.

Taipale, R. S., & Häkkinen, K. (2013). Acute Hormonal and Force Responses to Combined Strength and Endurance Loadings in Men and Women: The "Order Effect." *PLoS ONE*, *8*(2), e55051. http://doi.org/10.1371/journal.pone.0055051

Tanner, J. M. (1962). Growth at Adolescent. *Oxford Publication*.

Taylor, M. J. D., Cohen, D., Voss, C., & Sandercock, G. R. H. (2010). Vertical jumping and leg power normative data for English school children aged 10–15 years. *Journal of Sports Sciences*, *28*(8), 867–872. http://doi.org/10.1080/02640411003770212

Taylor, T., West, D. J., Howatson, G., Jones, C., Bracken, R. M., Love, T. D., … Kilduff, L. P. (2015). The impact of neuromuscular electrical stimulation on recovery after intensive, muscle damaging, maximal speed training in professional team sports players. *Journal of Science and Medicine in Sport*, *18*(3), 328–332. http://doi.org/10.1016/j.jsams.2014.04.004

Temfemo, A., Hugues, J., Chardon, K., Mandengue, S. H., & Ahmaidi, S. (2009). Relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls. *European Journal of Pediatrics*, *168*(4), 457–464. http://doi.org/10.1007/s00431-008-0771-5

Thompson, A., & Taylor, B. N. (2008). Guide for the Use of the International System of Units (SI). *Special Publication (NIST SP) - 811*. http://doi.org/200349

Thorlund, J. B., Aagaard, P., & Madsen, K. (2009). Rapid muscle force capacity changes after soccer match play. *International Journal of Sports Medicine*, *30*(4), 273–278. http://doi.org/10.1055/s-0028-1104587

Thorlund, J. B., Michalsik, L. B., Madsen, K., & Aagaard, P. (2008). Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scandinavian Journal of Medicine and Science in*

Sports, 18(4), 462–472. http://doi.org/10.1111/j.1600-0838.2007.00710.x

Tillin, N. A., Pain, M. T. G., & Folland, J. (2013). Explosive force production during isometric squats correlates with athletic performance in rugby union players. *Journal of Sports Sciences, 31*(1), 66–76. http://doi.org/10.1080/02640414.2012.720704

Tillin, N. A., Pain, M. T. G., & Folland, J. P. (2012). Contraction type influences the human ability to use the available torque capacity of skeletal muscle during explosive efforts. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1736), 2106–2115. http://doi.org/10.1098/rspb.2011.2109

Ugrinowitsch, C., Tricoli, V., Rodacki, A. L. F., Batista, M., & Ricard, M. D. (2007). Influence of Training Background on Jumping Height. *The Journal of Strength and Conditioning Research*, *21*(3), 848. http://doi.org/10.1519/R-20162.1

Vanrenterghem, J., De Clercq, D., & Van Cleven, P. (2001). Necessary precautions in measuring correct vertical jumping height by means of force plate measurements. *Ergonomics*, *44*(8), 814–8. http://doi.org/10.1080/00140130118100

Veilleux, L. N., & Rauch, F. (2010). Reproducibility of jumping mechanography in healthy children and adults. *Journal of Musculoskeletal Neuronal Interactions*, *10*(4), 256–266.

Viru, A., Loko, J., Harro, M., Volver, A., Laaneots, L., & Viru, M. (1999). Critical Periods in the Development of Performance Capacity During Childhood and Adolescence Critical Periods in the Development of Performance Capacity During Childhood and Adolescence. *European Journal of Physical Education*, *4*(4), 75–119. http://doi.org/10.1080/1740898990040106

Walsh, M. S., Böhm, H., Butterfield, M. M., & Santhosam, J. (2007). Gender Bias in the Effects of Arms and Countermovement on Jumping Performance. *The Journal of Strength and Conditioning Research*, *21*(2), 362. http://doi.org/10.1519/R-19825.1

Walters, O. W. M. (2017). *The Validity and Reliability of a Novel Video Based Method to Measure Flight Time and Jump Height in a Paediatric Population. Unpublished Master's Thesis.* Swansea University, UK.

Watkins, J. (2010). *Structure and function of the musculoskeletal system* (2nd ed.). Human Kinetics.

Watkins, J. (2014). *Fundamental biomechanics of sport and exercise*. Routledge.

Weeks, B. K., Young, C. M., & Beck, B. R. (2008). Eight Months of Regular In-School Jumping Improves Indices of Bone Strength in Adolescent Boys and Girls: The POWER PE Study. *Journal of Bone and Mineral Research*, *23*(7), 1002–1011. http://doi.org/10.1359/jbmr.080226

Weir, J. P. (2006). Is fatigue all in your head? A critical review of the central governor model. *British Journal of Sports Medicine*, *40*(7), 573–586. http://doi.org/10.1136/bjsm.2005.023028

West, D. J., Cook, C. J., Stokes, K. A., Atkinson, P., Drawer, S., Bracken, R. M., & Kilduff, L. P. (2014). Profiling the time-course changes in neuromuscular function and muscle damage over two consecutive tournament stages in elite rugby sevens players. *Journal of Science and Medicine in Sport*, *17*(6), 688–692. http://doi.org/10.1016/j.jsams.2013.11.003

West, D. J., Cunningham, D., Bevan, H. R., Crewther, B., Cook, C., & Kilduff, L. (2013). Influence of active recovery on professional rugby union player's ability to harness postactivation potentiation. *Journal of Sports Medicine and Physical Fitness*, *53*(2), 203–208.

West, D. J., Owen, N. J., Jones, M. R., Bracken, R. M., Cook, C. J., Cunningham, D. J., … Kilduf, L. P. (2011). Relationships between force-time characteristics of the isometric midthigh pull anddynamic performance in professional rugby league players. *Journal of Strength and Conditioning Research*, *25*(11), 3070–3075. http://doi.org/10.1519/JSC.0b013e318212dcd5

Whitmer, T., Fry, A. C., Forsythe, C., Andre, M. J., Lane, M. T., Hudy, A., & Honnold, D. (2014). Accuracy of a Vertical Jump Contact Mat for Determining Jump Height and Flight Time. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *29*(4), 877–881. http://doi.org/10.1519/JSC.0000000000000542

Wilson, G. J., Newton, R. U., Murphy, A. J., & Humphries, B. J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine & Science in Sports & Exercise*, *25*(11), 1279???1286. http://doi.org/10.1249/00005768-199311000-00013

Winter, E. M., Abt, G., Brookes, F. B. C., Challis, J. H., Fowler, N. E., Knudson, D. V, … Yeadon, M. R. (2015). *Misuse of "Power" and other mechanical terms in Sport and Exercise Science Research*. *Journal of Strength and Conditioning Research* (Vol. 30).

http://doi.org/10.1519/JSC.0000000000001101

Wright, G. a, Pustina, A. a, Mikat, R. P., & Kernozek, T. W. (2011). Predicting Lower Body Power From Vertical Jump Prediction Equations for Loaded Jump Squats At Different Intensities in Men and Women. *Journal of Strength and Conditioning Research*, *26*(3), 1. http://doi.org/10.1519/JSC.0b013e3182443125

Chapter 10 Appendix

Appendix I: Participant Consent Form

TO BE COMPLETED BY THE PARENTS, GUARDIANS OF PARTICIPANTS

Contact Details:

Mr Nicholas Owen, School of Engineering, Swansea University: n.j.owen@swansea.ac.uk
Tel: [redacted] (University)

Chris Jones, School of Engineering, Swansea University: 551514@Swansea.ac.uk

Study title

Biomechanical assessment of muscle function in children aged 7 to 11 years (Key Stages 1 & 2)

Please initial box

1.	I confirm that I have read and understood the information sheet dated 26-11-12 for the above study and have had the opportunity to ask questions.	
2.	I understand that my child's participation is voluntary and he/she is 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 Swansea University and/or physiotherapists from ABM NHS Trust Paediatric Physiotherapy Unit. I give permission for these individuals to have access to these records.	
4.	I give permission for my child to take part in the above study.	

_______________________________ ________________ ______________________

Name of Parent/Guardian/Head teacher Date Signature

_______________________________ ________________ ______________________

Researcher Date Signature

Appendix II: Parental Information Sheet

Parental/Guardian Information Sheet (Version 1.1, Date: 05/01/2015)

Project Title:

Investigating the suitability of neuromuscular variables for the assessment of coordination and coordination deficits in paediatric populations.

Contact Details:

Mr Nicholas Owen, (Academic Supervisor), Swansea University: n.j.owen@swansea.ac.uk, [redacted]

Mr Chris Jones (PhD Student), Swansea University: 551514@swansea.ac.uk

1. Invitation Paragraph

We are looking for participants from Primary School aged between 7 to 11 years old, to take part in our study in which we are examining the ability of jumping to measure movement for children. Please take time to read through the following information thoroughly and feel free to contact us if you have any queries about this study.

2. What is the purpose of the study?

The purpose of this study is to gather data regarding normal healthy children's movement pathways so that we can develop a measure to help identify children with motor learning disorders such as DCD. Your cooperation in the study will enable us to gather representative data for children so that we will be able to screen in the future for children with movement disorders such as Developmental Coordination Disorder (DCD which impacts around 5-8% of the global population.

3. Why has your child been chosen?

Your child has been chosen because they are in the required age range and are attending Tonnau Primary School. Participation is voluntary and if your child helps in this project but then changes their mind, may withdraw at any time during the study without being questioned or being required to provide an explanation.

4. What will your child be required to do?

1. All procedures will take place in your child's school in the presence of a teacher.

2. All procedures have been approved by a paediatric physiotherapist.

3. All procedures will be under the supervisor of a first aid trained teacher/researcher.

4. The date of birth, height, and weight of your child will be recorded.

5. After a familiarized warm up activity and being shown what to do, your child will be requested to perform 2 standing jumps on a floor-mounted platform. 30 seconds rest will be given between trials. A force platform is a flat metal plate (60cm x 40cm x 6cm) which measures how hard your child pushes against the floor.

5. What are the possible disadvantages of taking part?

Jumping is a natural feature of free play; therefore the risk of injury or discomfort to your child, arising from performance of the jump, is unlikely to be greater than that presented by free play. Your child will be supervised at all times by a member of the school staff and research team who are first aid certified.

6. What are the possible benefits of taking part?

The aim of this project is to measure children with normal levels of movement ability, which will then help us to screen children in future for conditions like developmental coordination disorder.

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

All data and participant information will be kept confidential and only be accessed by the research team. All data will be kept on a password protected computer and stored in a digital format to avoid identification to the participant. When the study and results are completed the data will be destroyed and removed in line with the guidelines of the biomechanics laboratory facilities in the College of Engineering, Swansea University.

8. What if I have any questions?

If you have any further questions please do not hesitate in contacting us by the details provided above provided at the top of the sheet.

Appendix III: Letter from Head Teacher and Opt Out Consent Form

To whom it may concern.

I have been asked by Mr. Nick Owen from the College of Engineering, Swansea University if it would be possible to use my school and pupils to help the development of a new physical test battery for children. I have read the draft proposal, 'Investigating the suitability of neuromuscular variables for the assessment of coordination and coordination deficits in paediatric populations', and The Governors and I are happy to cooperate with the proposed testing.

I will ensure that we have parental consent for every child who is to take part.

Yours sincerely,

Head teacher's signature: ________________

Dear Parent

Swansea University are planning on carrying out jump test at our school on the 9th of January. The tests are very simple and will only require your child to jump off a floor metal plate, after some warm-up activities. Each child will need to complete two jumps. The metal plate measures how you hard your child pushes against the floor. The purpose of the tests is to help develop assessments for diagnosis of coordination problems in young children and is being carried out with the help of Neath Port Talbot Children's Therapy Centre.

After the jump testing staff and students from Swansea University will be providing an activity for the pupils. All pupils are welcome to attend the activity (Real Tudor History)

If you **do not** want your child to take part in the jumping assessments could you please complete the form below.

I do not what my child:

Child's name _ Date of birth _ _ _ _ _ _

Appendix IV: DBS/DRB Certificate

Enhanced Certificate
Page 1 of 2

Disclosure & Barring Service

Certificate Number [redacted]

Date of Issue: 26 MARCH 2015

Applicant Personal Details

Surname: JONES

Forename(s): CHRISTOPHER MARK

Other Names: NONE DECLARED

Date of Birth: [redacted]

Place of Birth: [redacted]

Gender: MALE

Employment Details

Position applied for:
CHILD WORKFORCE PHD

Name of Employer:
SWANSEA UNIVERSITY

Countersignatory Details

Registered Person/Body:
SWANSEA UNIVERSITY

Countersignatory
KERAN WILLIAMS

Police Records of Convictions, Cautions, Reprimands and Warnings

NONE RECORDED

Information from the list held under Section 142 of the Education Act 2002

NONE RECORDED

DBS Children's Barred List information

NONE RECORDED

DBS Adults' Barred List information

NOT REQUESTED

Other relevant information disclosed at the Chief Police Officer(s) discretion

NONE RECORDED

Enhanced Certificate

This document is an Enhanced Criminal Record Certificate within the meaning of sections 113B and 116 of the Police Act 1997

Appendix V: Extension to Review of Literature

Newton's Laws of Motion

Human locomotion is not a simple rigid system and by nature is very complex. The basis of how all human locomotion is quantified is an integral part of research and sports medicine (Winter et al., 2015). To improve our knowledge and understanding of factors that influence the ability to perform exercise or human locomotion an understanding of the three laws motion is needed, as Newtonian mechanics is fundamental to all forms of motion. Newton's laws of motion was first present by Newton in 1667 in his 3-volume *Philosophiae Naturalis Principia Mathematica* (Newton, 1667).

Newton's First Law of Motion

The First Law of Motion is commonly called the "Principle of Inertia" and is described as

> "Everybody continues in its state of rest, or uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it" (Newton, 1667).

Newton's Second Law of Motion

The Second Law of Motion is referred to as the impulse-momentum relationship, and is described as

> "The change of motion is proportional to the motive force impressed; and is made in the direction off the right line in which that force is impressed" (Newton, 1667).

To note the definition of motion, expression used in the Principia (Newton, 1667), is equivalent to the term momentum in more modern mechanics and is measured by the product of the change in velocity and the quantity of matter (mass), in addition to the magnitude and duration of the force. The magnitude and duration of the force is also referred to as the impulse, which is measured by the product of force (N) and time (s).

Newton’s Third Law of Motion

The Third Law of Motion is referred to as the action-reaction pairs and states

> “To every action there is always opposed an equal reaction: or, the mutual action of two bodies upon each other are always equal, and directed to contrary parts” (Newton, 1667).

For example, when taking a penalty kick in football the ball will remain resting on the penalty spot until an unbalanced form is impressed upon it, which would be the force from the foot applied to ball when performing a kicking action.

This statement can be expressed algebraically as:

$$J = \Delta P$$

Equation 7

Where J = impulse of the object (N.s) and ΔP = change in momentum (kg. m.s^{-1}) of the object, this can also be represented algebraically as

$$F \cdot t = m \cdot v - m \cdot u$$

Equation 8

Where F = magnitude of the force (N), t = duration of the force (s), m = mass of object (kg), u velocity of object immediately prior to application of the force (m.s^{-1}), and v = velocity of object immediately after the removal of the force (m.s^{-1}). This is often expressed as:

$$F = \frac{m \cdot (v - u)}{t}$$

Equation 9

Since change in velocity over time is acceleration it follows that Equation 3 can be written as and can be explained by Newtons Second law of motion as a product of the objects mass and acceleration (Newton, 1667). This is algebraically represented as:

$$F = m \cdot a$$

Equation 10

Where F = force (N), m = mass of the object (kg)

Definition of Key Variables

Force

Force is ubiquitous and is essential for all life from holding atoms and cells together to influencing changes in motion in the human body to holding the planets and solar system together. When discussing human movement force is defined as that which alters or tends to alter a body's state of rest or type of movement or shape (Watkins, 2010, 2014).

Work Done

The work done by the body is quantified as the product of the force and the distance moved by the point of application of the force with no limitation on time (Komi, 1992). This is expressed algebraically as:

$$WD = F \cdot d$$

Equation 11

Where WD = work done (J), F = average force exerted to an object or person (N) and is distance the object has travelled (m).

At any particular instant in time, the total mechanical energy or work done by an object is the sum of its kinetic energy (translational and rotational) and its gravitational potential energy (Watkins, 2014).

Mechanical Power

In terms of human motion, power can be defined as the rate of transformation of energy from one form to another. Mechanical power (termed power hereafter) is the rate at which energy is transformed in the form of work (Komi, 1992; Watkins, 2014). Power can therefore be defined as the rate at which chemical potential energy at a cellular level is transformed to kinetic energy in terms of human locomotion and movement. The SI system the unit of power is the watt (W, or $J.s^{-1}$, or $kg.m^{2}.s^{-3}$), this can be expressed algebraically as:

$$P = \frac{WD}{t}$$

Equation 12

Where P = power (W), WD = work done (N.m), and t = time (s). As work done is $F \cdot d$ this equation can therefore, be expressed as:

$$P = \frac{F \cdot d}{t}$$

Equation 13

Where P = power (W), F = force (N), d = distance (m) and t = time (s). As distance over time is velocity, power can be expressed algebraically as:

$$P = F \cdot v$$

Equation 3

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

Power can be reported in a number of ways such as average power or instantaneous power. Average power identifies the mean power output over a selected period of time. Whereas, instantaneous power identifies power for one given instant. An instant is an infinitesimally small point in time that has no duration, therefore it is theoretically impossible to measure instantaneous power. When instantaneous power is measured, this is actually average power but over a very short duration. The duration is typically determined as one sample in the sampling frequency.

Accounting for Body Size: Normalising and Allometric Scaling

Neuromuscular performance tests such as a countermovement jump and an isometric mid-thigh pull from a force platform are commonly used to assess muscular strength and function (Owen et al., 2014; West et al., 2011). These tests provide normative data values for various groups of athletes, evaluate the success of training and rehabilitation procedures, and evaluate the performance capabilities for sport and work related activities (Abernethy, Wilson, & Logan, 1995; Duncan, Hankey, & Nevill, 2013; Hogan, 1991; Markovic & Jaric, 2004; Nevill, Holder, Baxter-Jones, Round, & Jones, 1998). A variety of factors may confound the neuromuscular performance variable from a test. These factors include sex, age, level of physical activity, technique, and body size (Jaric, Mirkov, & Markovic, 2005). Body size represents a factor that is generally believed to affect the outcome of physical performance (Cleather, 2006;

Jaric, 2002; Jaric et al., 2005). For the purpose of this thesis body size is defined as the physical measurement of the body, examples of body size measurements are body mass, body weight and stature. Researchers often compare and are interested in importance of different body sizes on performance, as a result a simple scaling method is typically employed by which performances are adjusted to allow the evaluation of the subject independent of body size. The most common scaling technique performed is by dividing the dependant absolute neuromuscular performance variable by the mass of the athlete (Cleather, 2006) to give a normalised neuromuscular performance value. This method can also be repeated to normalise neuromuscular performance values by body weight and stature. This approach is known as the ratio method or the per ratio standard. The use of absolute and normalised has been used interchangeably with CMJ neuromuscular performance in the child populations. For example, a study by Focke et al, (2013) investigated the effects of age, sex and activity level on CMJ performance in children and adolescents. The results of show that absolute jump height (JH) increases significantly with age, in addition to males having significantly higher values than females. However, when JH was normalised to body height, the influence of age was ameliorated though the sex differences were maintained. Focke et al, (2013) also investigated normalised Fmax and peak RFD but did not report the absolute values. This is supported by the findings of Sumnik et al, (2013) who used for jumping mechanography in healthy children and adolescents aged 6-18 years, to highlight that absolute peak power and Fmax were strongly dependent on age and weight for both sexes. Sex differences were only observed over the age 13 years at which point boys demonstrating significantly higher CMJ neuromuscular performance vales than girls. In contrast, peak power normalised to body mass and Fmax normalised to BW remained nearly constant with respect to age and sex. However, the per ratio standard method is only valid if the relationship between body size and the neuromuscular performance variable is linear. As a result the use of the ratio method has come under strong criticism as the relationship between neuromuscular performance and body size is not directly proportional (Jaric, 2002; Jaric et al., 2005; Nevill & Holder, 1995). Consequently, the use of the statistical method allometric scaling or modelling has been deemed a more suitable and valid method for removing the influence of body size (Nevill & Holder, 1995)(Nevill & Holder, 1995). Allometric modelling is based on the use of the mathematical relationship to scale neuromuscular performance by body size.

$$y = a \cdot x^b$$

Equation 14

Whereby y = absolute neuromuscular performance value, a = allometric scaled neuromuscular performance value, x = body size and b = constant.

When normalisation is employed it presumes that the constant b = 1, whereas in strength testing for example allometric modelling identifies the constant b = 0.66 (Cleather, 2006). Allometric modelling identifies the relationship between the dependent neuromuscular performance variable and the body size variable via logarithmic transformation. Logarithmic transformation provides a linear model symmetrically distrusted (Figure 10.2). This is algebraically represented as:

$$\log y = \log a + \log BM$$

Equation 15

Whereby y = neuromuscular performance value, a = intercept value and BM = body mass.

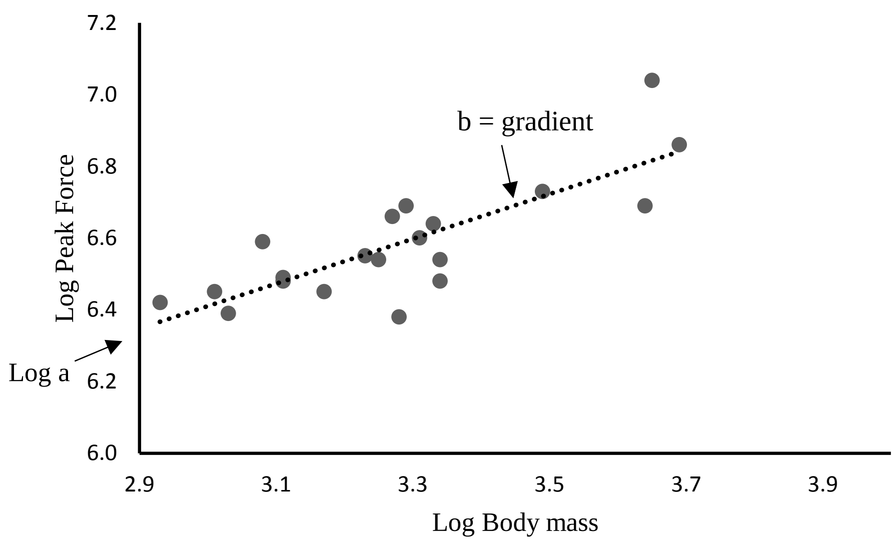

Figure 10. 1. Log transformed peak force and body mass values for boys in school year 3

As a result allometric models naturally helps to overcome the heteroscedasticity, non-normality and skewness observed with per ratio variables (Nevill & Holder, 1995). Allometric modelling is therefore deemed a more appropriate and valid method of evaluating neuromuscular performance variables independent of body size (Cleather, 2006; Jaric et al., 2005; Markovic & Jaric, 2004; Nevill & Holder, 1995). However, it has previously been demonstrated that a body mass bias can exist when using allometric modelling (Batterham & George, 1997; Cleather, 2006). For example, Batterham & George (1997) examined the raw residuals (actual lifting performance minus predicted lifting performance) of an allometric fit to performances of male and female medallists at the 1995 World Weightlifting Championships and highlighted that allometric modelling penalized the performance of lighter and heavier lifters.

Limited research exists for the measurement of allometrically scaled CMJ neuromuscular performance variables measured via a FP. A study by Fricke, Stabrey, Tutlewski & Schoenau. (2009) examined mechanographic analysis of allometric scaled CMJ Fmax and its relationship to maximal isometric grip force (MIGF) in 312 German primary school children. The findings of the study demonstrated that MIGF was a good predictor and explained for some of the variance of CMJ scaled Fmax in healthy children but not in unconditioned children. Duncan, Hankey, Lyons, James & Nevill. (2013) investigated peak power prediction in junior basketballers, and compared linear and allometric models to predict peak power. The author's concluded that the allometrically scaled regression model may provide a biologically sound and more accurate estimation of peak power in adolescent basketball players. Likewise, using a multiplicative model (CMJ height and body mass) provides a similar estimate of peak power in elite junior basketball players that was more accurate than other commonly used linear additive prediction models. A more recent study by Raffalt, Alkjaer & Simonsen. (2016b) demonstrated that JH was significantly higher and with less variation in 20 male adults when compared to 11 male children, whereas allometrically scaled knee joint power and Fmax was greater in children but this was only reported graphically.

Appendix VI: Additional Methods

Warm Up

Table 10. 1. Standardized warm up prior to data collection.

Exercise	**Additional notes**
Skips x 2 reps over 10m	-
Jog x 2 reps over 10m	This was called the caterpillar train for children aged 7 to 11 years
Body weight squats x 10 reps	-
Lunges x 5 reps each side	-
Pogo's x 10 reps	This was called bunny hops when testing children aged 7 to 11 years
Bounds x5 reps	This was called kangaroo hops when testing children aged 7 to 11 years
Countermovement Jump	Instruction was to jump as high as you can whilst keeping your hands on your hips

Numerical Integration

A countermovement jump (CMJ) force-time history data can be used to analyse determine other variables such as impulse, velocity, displacement and power can be determined using numerical integration. Numerical integration or forward dynamics is a process which calculates the area under the graph of the force-time history. The area under a force-time history is referred to as impulse.

As Newton's second law states a force acts on an object the change in linear momentum experienced by the object takes place in the direction of the force and is proportional to the impulse (Newton, 1667). Therefore impulse can be expressed mathematically as:

$$J = \Delta P$$

Equation 7

Where J = impulse (N.s) and P = momentum (kg.m.s^{-1}), as impulse is a product of force and time and change in momentum is a product of the objects mass and change in velocity. This can be expressed algebraically as:

$$F \cdot t = m \cdot v - m \cdot u$$

Equation 8

Where F = force (N), t = time (s), m = mass of object (kg) and Δv = change in velocity. If the mass of the object is known and doesn't change, Δv can be expressed algebraically as:

$$\Delta v = \frac{F \cdot t}{m}$$

Equation 16

Where I = impulse, F = force (n), t = time (s), m = mass of object (kg) and Δv = change in velocity, from which the equations of motion and power can be used to calculate variables such as jump displacement and instantaneous peak mechanical power.

When a participant stands on a force platform, the vertical component of the ground reaction force (VGRF) and the participant's weight to be acting on the participant's whole body centre of gravity (CoG). It is assume that body mass remains constant, therefore any changes in the VGRF is a result of a change in acceleration of the CoG. The change in force past bodyweight is also known as the resultant force or net force acting on the CoG. The resultant force can then be utilized in the impulse-momentum method to attain change in velocity for a given interval or sample. If these samples are small then it can be considered that the velocity determined at the end of each time interval represents the instantaneous velocity at that point. Thus, the VGRF can be integrated at a high sampling frequency (typically 1000 Hz), where the change in velocity for each sample width being added to the previous value of velocity. This then gives the value of velocity at the end of the sample width being integrated in this way an instantaneous velocity/time history for the participant's CoG can be determined. Therefore, in order to find the take-off velocity of the participant's CoG the area between a graph of the VGRF and the time axis must be found for each sample and accumulated to the point of take-off. This is algebraically represented as:

$$v_{ti} = v_{ti-1} + \int_{ti-1}^{ti} (F_z - m \cdot g) dt \cdot \frac{1}{m}$$

Equation 17

Where v_{ti} = change in velocity interval ($m.s^{-1}$) Fz = vertical force (N), g = gravity (9.81 $m.s^{-2}$), m = body mass (kg).

If a signal 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 a countermovement jump where an equation does not have a standard integral or no equation is known, therefore other methods must be applied. There are a two main methods of numerical integration for calculating the area under a graph, 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 fixes an approximation to the area under the graph. 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 10.2). It is not know which method best represent the actual force-time history. The Simpson's rule gives a better approximation of the area than the trapezoidal rule if the same number of strips are used, however the trapezoidal rule will give the exact area of each strip. This must be considered when determining which measure will give a true representation of the force-time curve.

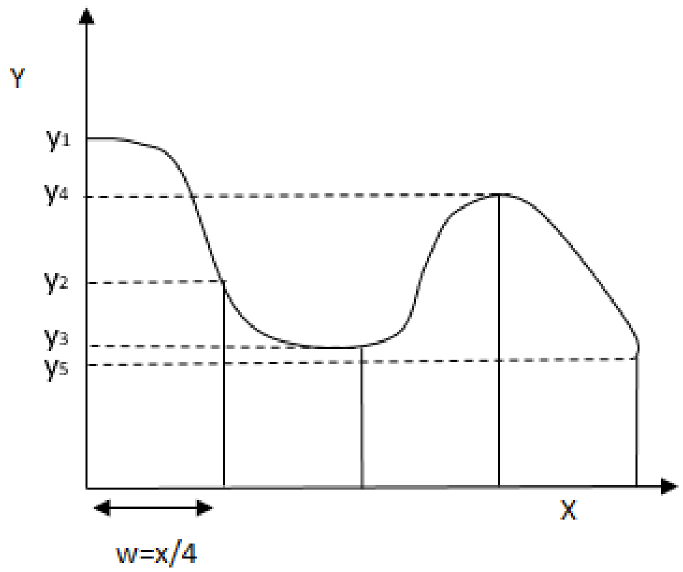

Figure 10. 2. Example of the use of trapezoidal rule and Simpson's rule to determine an aapproximate area under a curve. Source: Owen. (2008)

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

Equation 18

$$Simpsons\ Rule\ area = \frac{1}{3}w(y_1 + y_5) + 4(y_2 + y_4) + 2(y_3)$$

Equation 19

Simpson's rule usually estimates the area with less error than the trapezoidal rule by fitting a curve to the end points of each pair adjacent strip's ordinates, 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 (Owen, 2008).

Numerical Differentiation

Numerical differentiation or inverse dynamics is a process by which the gradient of a curve can be determined, for example when using inverse dynamics of displacement-time to attain a change in velocity-time graph (Figure 10.3). This process is normally undertaken when kinematic data is collected. For example, attaining velocity from change in displacement of the barbell from a linear position transducer.

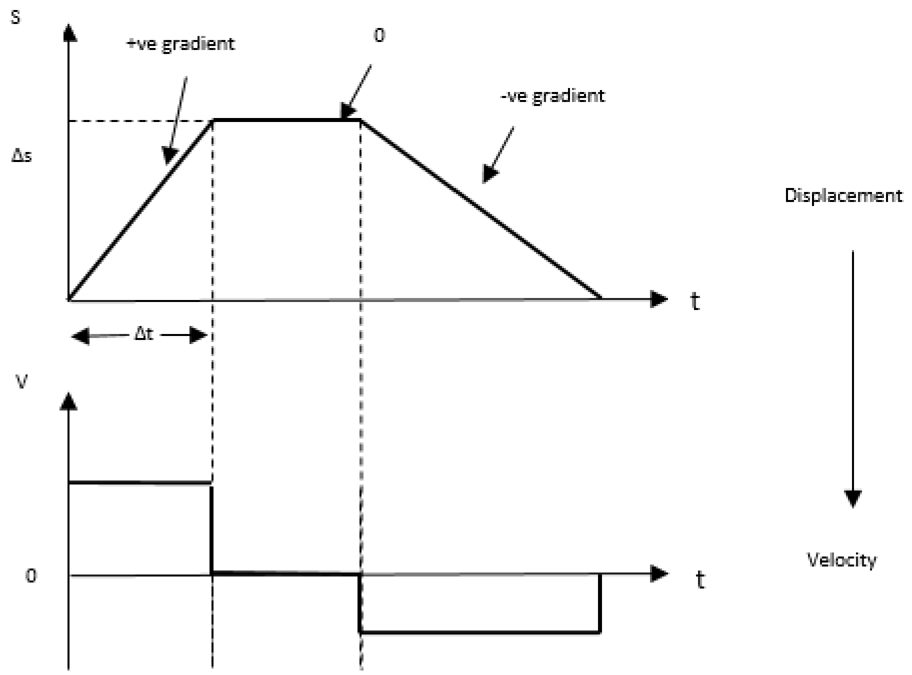

Figure 10. 3. Process of inverse dynamics of displacement-time data to attain velocity time data

Firstly it is much easier and cheaper to attain kinematic data rather kinetic data, however there are issues with noise and filtering when using inverse dynamics on the kinematic data. The application of inverse dynamics will introduce error and remove some of the signal and thus change the true representation of the data. If the gradient of the data was linear and the motion can be described by an equation analytical differentiation can be used. However, this is not the case for human movement such as jumping and sprinting.

Alternatively average values of the gradient could be taken if the time interval is kept small, the average value of the gradient gives a very good approximation of the data point at the centre of the time interval. The value would represent the average gradient between the two time points and therefore would be most likely correct. To produce differentiated values that correspond to the original sampling frequency the following formula is used, this type of differentiation is known as the central difference method where the force gradient, dF/dt is calculated from:

$$\frac{dF_x}{dt}\ (t) = \frac{F_x(t+1\ sample)\cdot F_x(t-1 sample)}{2\cdot\Delta t}$$

Equation 20

$$\frac{dF_y}{dt}\ (t) = \frac{F_y(t+1\ sample)\cdot F_y(t-1 sample)}{2\cdot\Delta t}$$

Equation 21

$$\frac{dF_z}{dt}\ (t) = \frac{F_z(t+1\ sample)\cdot F_z(t-1 sample)}{2\cdot\Delta t}$$

Equation 22

$$\frac{dF}{dt(t)} = \sqrt{\frac{dF_x^2}{dt(t)} + \frac{dF_y^2}{dt(t)} + \frac{dF_z^2}{dt(t)}}$$

Equation 23

Whereby dF/dt = 1st derivate of force, Δt = sampling interval = 1/ Sampling rate.

Appendix VII: Extension to Experimental Chapters

Experimental Chapter 1: Unprocessed and Processed Countermovement Jump Variables

Table 10. 2. Unprocessed and processed countermovement jump variables

Variable (Abbreviation)	Units	Unprocessed or processed	Definition and analysis of variable	Requires start time prior to calculation
Peak Force (Fmax)	N	Unprocessed	The sample with the highest numerical value during the CMJ from the sampling period of the force-time history	No
In-jump minimum force (IMF)	N	Unprocessed	The sample with the lowest numerical value prior to Fmax during the sampling period of the force-time history	No
In-jump force range (IFR)	N	Unprocessed	The difference between IMF and Fmax	No
Basic rate of force development (BRFD)	$N.s^{-1}$	Unprocessed	The IFR divided by the time difference between IFR	No
Bodyweight (BW)	N	Unprocessed	Mean value of VGRF during a 1 second period of quiet standing of the CMJ (Analysis performed prior to command to jump)	Yes
Eccentric and Concentric Impulse (J)	N.s	Processed	Cumulative impulse between imitation start time to eccentric to concentric changeover time, cumulative impulse eccentric to concentric changeover time to time at take-off	Yes

Jump height (JH)	m	Processed	Peak vertical displacement of the body's centre of gravity from the sampled displacement-time history	Yes
Peak mechanical power (PPO)	W	Processed	The highest numerical value obtained from the sampled power-time history	Yes
Peak rate of force development (RFD)	$N.s^{-1}$	Processed	The maximum (concentric)and minimum (eccentric) numerical value obtained from the sampled rate of force-time history	Yes

Appendix VIII: Results for Experimental Chapter 1

	N	BW (N)	IMF (N)	Fmax (N)	IFR (N)	BRFD (N.s^{-1})		N	BW (N)	IMF (N)	Fmax (N)	IFR (N)	BRFD (N.s^{-1})
Boys	1	320	142	1064	922	0.179	Girls	41	587	316	1461	1144	0.185
	2	285	136	678	542	0.384		42	459	179	1063	883	0.296
	3	269	113	810	697	0.233		43	362	194	1080	886	0.192
	4	350	160	1059	899	0.206		44	440	117	1112	994	0.292
	5	431	109	917	807	0.424		45	517	-1	1351	1352	0.247
	6	354	182	1203	1021	0.164		46	343	163	921	758	0.295
	7	432	199	1199	1000	0.241		47	366	129	748	619	0.284
	8	375	136	929	793	0.244		48	310	109	984	875	0.226
	9	377	228	1070	842	0.315		49	429	184	1069	884	0.220
	10	375	139	940	800	0.270		50	287	156	649	493	0.412
	11	360	218	825	607	0.289		51	227	74	618	544	0.232
	12	281	158	708	549	0.236		52	234	54	730	676	0.189
	13	433	334	1228	894	0.300		53	244	115	486	371	0.315
	14	299	108	836	728	0.243		54	447	275	916	640	0.369
	15	333	164	922	922	0.274		55	368	210	979	769	0.292
	16	248	37	589	551	0.210		56	213	87	731	643	0.167
	17	242	109	533	423	0.453		57	278	132	654	521	0.274
	18	287	158	822	633	0.272		58	199	108	631	523	0.163
	19	213	107	746	639	0.145		59	248	125	696	571	0.277
	20	232	47	630	583	0.175		60	321	95	840	745	0.184
Elite Males	21	1009	625	2442	1796	0.454	Elite Females	61	615	320	1145	1125	0.314
	22	824	501	2144	1643	0.593		62	759	249	1705	1456	0.260
	23	949	130	2326	2196	0.538		63	696	157	1596	1439	0.452
	24	860	159	2717	2558	0.262		64	690	115	1719	1603	0.233
	25	731	280	1573	1292	0.608		65	884	248	2185	1936	0.274
	26	881	346	2238	1891	0.367		66	861	42	1793	1450	0.297
	27	861	347	2164	1816	0.335		67	832	267	1741	1473	0.525
	28	829	28	2266	2238	0.245		68	757	69	1607	1538	0.218
	29	842	155	2250	2095	0.368		69	665	190	1429	1239	0.309
	30	969	443	2171	1728	0.686		70	589	288	1414	1125	0.364
	31	1114	132	3095	2963	0.274		71	630	299	2041	1742	0.220
	32	1162	329	2913	2584	0.295		72	760	101	1787	1686	0.287
	33	1058	167	2752	2585	0.283		73	678	209	1691	1482	0.224
	34	1017	328	2643	2314	0.375		74	629	249	1616	1367	0.244
	35	1018	228	2941	2712	0.290		75	702	93	2016	1922	0.180
	36	1166	459	2879	2420	0.378		76	643	280	1625	1345	0.326
	37	1214	340	2824	2484	0.395		77	776	279	1630	1351	0.362
	38	1103	473	2488	2014	0.388		78	654	126	1387	1260	0.336
	39	1157	63	2947	2883	0.310		79	726	20	1803	1782	0.257
	40	927	313	2639	2326	0.324		80	658	212	1557	1344	0.256

Table VIII.1: Raw CMJ data collected for analysis, BW = bodyweight, IMF = in-jump minimum force, Fmax = peak force, IFR = in-jump force range, BRFD = basic rate of force development.

Appendix IX: Results for Experimental Chapter 2

	N	BW (N)	IMF (N)	Fmax (N)	IFR (N)	BRFD ($N.s^{-1}$)		N	BW (N)	IMF (N)	Fmax (N)	IFR (N)	BRFD ($N.s^{-1}$)
Year 3 Girls	1	276	84	695	611	3102	Year 5 Girls	81	329	126	780	653	2120
	2	258	92	780	688	3406		82	452	226	1090	863	2345
	3	184	75	614	538	3040		83	225	16	918	902	7982
	4	213	87	731	643	3850		84	361	97	924	827	3321
	5	378	99	1140	1040	5778		85	343	163	921	758	2569
	6	278	132	654	521	1901		86	428	115	1235	1120	6914
	7	269	37	736	699	3478		87	335	171	904	732	2533
	8	221	56	652	596	3569		88	366	129	748	619	2180
	9	274	52	767	715	4387		89	328	136	974	838	3741
	10	221	117	658	541	3127		90	222	83	744	660	4000
	11	373	189	806	616	2161		91	395	254	1147	892	3611
	12	199	108	631	523	3209		92	310	109	984	875	3872
	13	248	125	696	571	2061		93	429	184	1069	884	4018
	14	253	104	695	590	2077		94	374	89	963	873	4079
	15	261	132	589	456	1382		95	450	271	1143	872	4360
	16	233	81	635	554	2473		96	287	156	649	493	1197
	17	263	10	806	795	4569		97	323	149	966	816	3813
	18	394	79	958	879	4803		98	336	72	809	737	2792
	19	321	95	840	745	4049		99	547	166	1558	1392	7444
	20	203	75	593	517	2439		100	263	59	899	829	5418
Year 3 Boys	21	324	99	1043	943	5894	Year 5 Boys	101	489	191	1342	1150	4772
	22	341	171	871	800	4233		102	359	152	1068	915	4067
	23	205	86	631	544	2286		103	491	282	1164	881	2851
	24	384	241	894	653	2687		104	623	364	1235	871	2647
	25	367	251	773	522	978		105	354	182	1203	1021	6226
	26	285	118	630	511	1271		106	575	278	1390	1111	3728
	27	248	37	589	551	2624		107	432	199	1199	1000	4149
	28	229	16	751	734	5206		108	375	136	929	793	3250
	29	271	113	600	486	1800		109	392	203	830	627	1583
	30	242	109	533	423	934		110	377	228	1070	842	2673

	31	222	68	838	770	6696		111	375	215	947	731	2107
	32	274	141	714	572	2279		112	515	234	1189	954	2710
	33	249	160	550	390	826		113	375	139	940	800	2963
	34	287	158	822	633	2327		114	330	215	764	548	1132
	35	235	14	645	631	3392		115	337	120	748	627	1823
	36	513	307	1011	703	2282		116	291	118	974	855	4150
	37	190	32	579	546	3085		117	531	257	1241	984	2491
	38	211	108	602	493	1988		118	252	140	660	519	1929
	39	213	107	746	639	4407		119	317	163	1086	922	4777
	40	232	47	630	583	3331		120	285	70	958	887	5280
Year 4 Girls	41	379	123	1112	988	5146	Year 6 Girls	121	308	76	787	711	2595
	42	294	99	873	774	4553		122	350	260	968	708	3324
	43	311	150	724	573	1642		123	548	291	1447	1155	4024
	44	226	48	784	735	4966		124	381	125	813	687	1766
	45	374	161	1037	876	3792		125	587	316	1461	1144	6184
	46	326	124	715	591	1646		126	487	182	1360	1178	7551
	47	227	74	618	544	2345		127	279	149	650	500	1786
	48	310	106	1031	924	7108		128	430	143	1302	1158	6542
	49	337	95	1093	997	5418		129	459	179	1063	883	2983
	50	278	778	778	650	3421		130	362	194	1080	886	4615
	51	234	54	730	676	3577		131	261	142	622	480	1383
	52	233	78	818	739	4799		132	337	12	1022	1010	5316
	53	244	115	486	371	1178		133	440	117	1112	994	3404
	54	300	81	616	534	1854		134	619	352	1595	1242	6149
	55	447	275	916	640	1734		135	326	184	780	595	2680
	56	231	90	754	664	4397		136	431	179	1027	847	2931
	57	282	43	660	617	2320		137	517	-1	1251	1352	5474
	58	368	210	979	769	2634		138	472	284	1165	880	2776

	59	253	91	721	630	2917		139	394	183	1137	954	4317
	60	289	32	1027	995	7316		140	557	288	1325	1037	4035
Year 4 Boys	61	324	99	1043	943	5894	Year 6 Boys	141	348	168	1044	874	3249
	62	304	139	1202	1063	10737		142	457	210	984	774	1783
	63	360	218	825	607	2100		143	327	66	606	984	8632
	64	279	23	962	929	7373		144	321	121	840	719	2297
	65	281	158	708	549	2326		145	320	142	1064	922	5151
	66	233	18	860	841	6050		146	388	110	858	747	2798
	67	379	262	896	634	1957		147	309	125	824	699	3107
	68	324	67	741	674	2832		148	403	144	1051	906	2895
	69	433	334	1228	894	2980		149	545	342	1246	903	3214
	70	299	108	836	728	2996		150	302	158	929	770	6417
	71	366	129	1005	875	3289		151	431	113	1160	1046	5779
	72	355	263	896	633	1912		152	305	216	727	510	1232
	73	416	216	890	674	1586		153	570	242	1415	1172	4014
	74	424	130	1002	872	2734		154	285	136	678	542	1411
	75	265	144	613	468	1449		155	381	150	855	704	1721
	76	279	169	897	728	3046		156	269	113	810	697	2991
	77	333	164	922	922	3365		157	312	82	745	662	2122
	78	308	99	801	701	3048		158	356	79	1008	929	3573
	79	271	200	656	456	1149		159	350	160	1059	899	4364
	80	284	104	721	616	1949		160	431	109	917	807	1903

Table IX.1: Raw CMJ data collected for analysis, BW = bodyweight, IMF = in-jump minimum force, Fmax = peak force, IFR = in-jump force range, BRFD = basic rate of force development.

Appendix X: Results for Experimental Chapter 3

	Subject	$F_{z\ max}$ (N)	$F_{zc\ max}$ (N)	$F_{zc\ max}$ as % of $F_{z\ max}$	Bodyweight (N)
Group 1	1	657	237	36%	271
	2	593	174	29%	204
	3	916	350	38%	448
	4	579	235	41%	191
	5	697	217	31%	249
	6	795	259	33%	366
	7	731	219	30%	235
	8	779	320	41%	278
	9	985	302	31%	339
	10	1092	345	32%	337
	11	632	191	30%	200
	12	589	203	34%	248
	13	631	217	34%	286
	14	895	274	31%	385
	15	815	310	38%	298
	16	709	360	51%	281
	17	1140	451	40%	378
	18	874	361	41%	294
	19	696	257	37%	276
	20	1043	305	29%	324
Group 2	21	831	353	42%	392
	22	1065	347	33%	320
	23	746	242	32%	313
	24	925	281	30%	362
	25	940	250	27%	375
	26	966	294	30%	323
	27	1390	436	31%	575
	28	930	340	37%	302
	29	1044	289	28%	349
	30	855	367	43%	382
	31	650	248	38%	288
	32	1027	424	41%	432
	33	813	214	26%	382
	34	660	183	28%	253
	35	968	312	32%	350
	36	749	356	48%	367
	37	1352	375	28%	518
	38	841	219	26%	322
	39	1090	436	40%	452
	40	1022	310	30%	338

Table X.1: Vertical ground reaction force data for countermovement jump for group 1 and group 2.

Group	Subject	Bodyweight (N)	$PP0_{1000}$ (W)	$PP0_{500}$ (W)	PPO_{250} (W)	PPO_{100} (W)	PPO_{50} (W)	PPO_{10} (W)
Group 1	1	271	1047	1051	1057	1074	1100	924
	2	204	685	688	692	706	724	502
	3	448	1148	1151	1155	1171	1195	1203
	4	191	677	671	678	680	702	678
	5	249	898	900	910	915	928	768
	6	366	1277	1280	1284	1302	1332	1116
	7	235	866	863	871	897	928	1073
	8	278	1118	1122	1125	1143	1148	1116
	9	339	1064	1068	1077	1101	1143	1172
	10	337	1475	1478	1490	1527	1550	1338
	11	200	533	537	545	567	582	661
	12	248	744	746	750	759	777	832
	13	286	941	944	947	957	970	762
	14	385	843	851	860	867	905	771
	15	298	1080	1083	1090	1116	1130	1172
	16	281	949	945	951	955	985	1092
	17	378	1449	1452	1462	1490	1531	1384
	18	294	937	940	947	967	995	902
	19	276	742	744	730	761	768	628
	20	324	1189	1195	1197	1252	1268	1280
Group 2	21	392	1073	1075	1080	1091	1102	1187
	22	320	1325	1327	1336	1361	1395	1495
	23	313	1117	1120	1127	1137	1175	1121
	24	362	1218	1221	1227	1239	1287	1241
	25	375	1466	1467	1474	1484	1518	1635
	26	323	1097	1102	1108	1127	1163	1043
	27	575	1608	1612	1624	1634	1675	1675
	28	302	830	836	845	870	894	810
	29	349	1463	1468	1478	1496	1538	1337
	30	382	1395	1398	1416	1432	1474	1410
	31	288	1083	1086	1090	1101	1121	1115
	32	432	1632	1636	1643	1666	1690	1682
	33	382	1268	1271	1277	1290	1307	1158
	34	253	921	924	927	944	958	1003
	35	350	1287	1289	1290	1327	1333	1190
	36	367	1086	1089	1090	1101	1111	1156
	37	518	2234	2239	2249	2270	2304	2283
	38	322	1385	1387	1395	1415	1453	1240
	39	452	1977	1982	1994	2031	2076	2092
	40	338	1538	1542	1551	1564	1598	1486

Table X.2: Peak vertical mechanical power produced in a countermovement jump for group 1 and group 2 sampled at 1000 Hz, 500 Hz, 250 Hz, 100 Hz, 50 Hz, and 10 Hz.

Time relative to t_s (ms)		-90	-80	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50
Group	Subject	Instantaneous power (W) [integration start time at t_s - 100 ms]														
Group 1	1	-1	-2	-3	-4	-5	-5	-5	-6	-5	-4	-2	1	6	11	18
	2	0	-1	-2	-2	-3	-3	-4	-4	-5	-6	-7	-9	-11	-12	-13
	3	0	0	0	1	1	1	1	1	1	0	-1	-2	-4	-5	-5
	4	0	0	0	0	0	-1	-2	-4	-5	-6	-8	-9	-10	-9	-6
	5	0	0	-1	0	0	1	2	4	6	10	15	22	30	38	48
	6	0	0	-1	-2	-3	-4	-4	-4	-5	-7	-8	-9	-7	-3	2
	7	-3	-4	-6	-6	-7	-7	-6	-5	-4	1	8	17	30	46	67
	8	0	0	-1	-1	-2	-3	-3	-3	-3	-2	0	4	8	15	23
	9	0	1	1	2	2	2	2	3	3	4	5	8	12	21	34
	10	1	1	1	1	0	0	-1	-1	-3	-5	-8	-10	-12	-14	-15
	11	0	0	0	0	0	0	-1	0	0	1	2	6	11	18	27
	12	0	0	-1	-1	-1	-1	-1	-2	-3	-4	-5	-6	-7	-8	-9
	13	0	1	2	3	4	5	6	7	9	11	13	17	21	27	33
	14	0	0	1	2	4	6	8	11	13	16	20	24	29	36	45
	15	0	0	1	1	1	2	2	3	4	5	6	8	10	13	16
	16	2	2	4	4	4	5	6	6	9	13	18	25	34	44	54
	17	1	1	2	2	3	3	4	5	5	6	8	10	12	14	16
	18	-1	-1	-2	-2	-2	-2	-2	-2	-1	0	1	3	4	5	5
	19	1	2	3	5	6	8	9	10	12	15	20	28	40	57	75
	20	1	3	4	6	7	8	10	11	14	20	28	40	55	73	95
Group 2	21	0	0	-1	-1	-1	-1	-2	-3	-3	-2	-1	3	8	16	27
	22	0	0	0	0	0	0	0	0	1	2	4	6	8	10	11
	23	0	0	0	0	0	-1	-1	-1	-2	-3	-4	-5	-7	-9	-11
	24	0	0	0	0	0	-1	-1	-2	-2	-4	-4	-5	-6	-6	-6
	25	-1	-2	-2	-3	-4	-5	-5	-5	-5	-3	-1	1	3	5	7
	26	0	0	0	-1	-1	-1	-2	-2	-2	-1	1	3	4	6	8
	27	0	0	1	1	1	1	2	3	5	7	11	16	23	32	41
	28	0	-1	-1	-1	-1	0	0	0	-1	-2	-3	-5	-7	-9	-11
	29	0	0	1	1	1	2	2	3	5	7	11	17	24	33	45
	30	0	0	0	0	0	0	0	0	1	2	5	9	14	22	32
	31	0	0	0	0	0	0	0	0	0	1	3	5	8	12	18
	32	0	0	0	1	1	1	0	0	0	-1	-2	-5	-8	-11	-16
	33	0	0	0	1	1	1	1	2	3	4	5	6	8	10	14
	34	0	1	2	2	2	2	2	3	4	6	9	13	21	32	46
	35	0	1	1	1	2	2	3	3	4	5	7	9	12	16	22
	36	0	1	1	1	1	1	1	0	0	-1	-2	-3	-3	-4	-4
	37	0	0	0	0	0	1	1	2	2	1	-2	-5	-10	-17	-25
	38	0	0	0	0	1	1	1	2	2	3	4	6	8	11	15
	39	0	0	0	0	0	1	2	3	5	9	13	19	27	38	52
	40	0	0	1	1	1	1	1	1	2	2	4	8	15	26	42

Table X.3: Instantaneous vertical mechanical power at times relative to t_s for group 1 and group 2 performing a countermovement jump.

Group	Subject	Simpson's Rule PPO_{500} (W)	Trapezoidal Rule PPO_{500} (W)
Group 1	1	1051	1044
	2	688	682
	3	1151	1146
	4	671	665
	5	900	894
	6	1280	1274
	7	863	858
	8	1122	1115
	9	1068	1059
	10	1478	1466
	11	537	530
	12	746	741
	13	944	939
	14	851	845
	15	1083	1075
	16	945	940
	17	1452	1443
	18	940	933
	19	744	739
	20	1195	1184
Group 2	21	1075	1070
	22	1327	1317
	23	1120	1115
	24	1221	1214
	25	1467	1462
	26	1102	1094
	27	1612	1601
	28	836	826
	29	1468	1456
	30	1398	1392
	31	1086	1081
	32	1636	1628
	33	1271	1265
	34	924	918
	35	1289	1278
	36	1089	1084
	37	2239	2230
	38	1387	1379
	39	1982	1977

	40	1542	1533

Table X.4: Peak vertical mechanical power produced from a countermovement jump for group 1 and 2. Peak power was determined using two different methods of numerical integration.

Appendix XI: Results for Experimental Chapter 4

	N	PP Act (W)	PP Est (W)		N	PP Act (W)	PP Est (W)
Year 3 Males	1	1191	1124		49	963	885
	2	645	667		50	921	878
	3	889	978		51	953	984
	4	1078	1319		52	754	658
	5	656	721		53	960	1038
	6	853	873		54	646	743
	7	959	953		55	1062	1077
	8	841	856		56	718	843
	9	856	904		57	606	818
	10	820	786		58	1060	899
	11	816	791		59	688	808
	12	969	1007		60	1057	993
	13	847	858		61	722	856
	14	1455	1457		62	853	829
	15	765	783		63	845	856
	16	1083	999		64	653	774
	17	625	734		65	843	732
	18	1064	968		66	1291	1391
	19	845	910		67	801	848
	20	671	720		68	739	773
	21	794	865		69	765	791
	22	856	1061		70	969	1029
	23	1095	909		71	711	838
	24	859	740		72	660	714
	25	726	738		73	1127	991
	26	1112	1048		74	678	756
	27	672	662		75	951	905
	28	1680	1483		76	670	797
	29	963	896		77	764	868
	30	860	792		78	899	928
	31	1091	1113		79	1055	937
	32	838	868		80	748	756
	33	994	931		81	1235	1110
	34	865	900		82	998	1034
	35	698	741		83	737	849
	36	1030	1121		84	908	854
	37	1884	1682		85	762	756

	38	712	790		86	1290	1419
	39	618	671		87	927	923
	40	913	892		88	906	956
	41	617	699		89	1018	904
	42	858	850		90	1002	792
	43	1138	1001		91	946	721
	44	895	916		92	764	687
	45	813	908		93	875	740
	46	1028	892		94	822	590
	47	674	841		95	869	671
	48	1118	1097		96	1021	1022