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A Biomechanical Investigation into Force, Power and Bone Morphology

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A Biomechanical Investigation into Force, Power and Bone Morphology

Nicholas John Owen

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

Swansea University
2018

Abstract

Force (*F*), produced by the neuromuscular system and transmitted by bones, is necessary for locomotion. Performance in activities of daily living and sport requires effective production and use of (*F*) for optimal outcomes. Quantifying neuromuscular performance, with *F* and force derived variables, allows monitoring of the effectiveness of training. Strength (S), power (*P*) and rate of force development (*RFD*) are important neuromuscular variables (NV) for predicting physical performance, which can be measured using a force platform (*FP*). This corpus comprises of 5 papers that examine different aspects of force in terms of human performance. Paper 1, investigated using postactivation potentiation (*PAP*), that may increase *P* temporarily, on international swimmers and the effect on start time compared to a traditional warm-up. There was no difference in start time although *P* was enhanced. PAP could be a useful alternative to a traditional warm-up. Paper 2, examined the relationship between isometric *F* variables and dynamic performance using new method of *F* analysis. Correlations were found between *RFD,* peak *F* and *F* at 100 ms vs.10 m sprint times and jump height. Paper 3, reported the first published criterion method for determining peak mechanical *P* (*Pp*) in a countermovement jump (CMJ), measured by a *FP,* with an accuracy < 1%. Paper 4, reported *Pp* normative values, which could be used to measure coordination and bone health in children, 7 to 11 years old, as existing, subjective measures are unreliable. Athletes' bones experience high forces, causing changes in their shape and composition. The Mary Rose skeletal collection comprises of 97 skeletons, some of which were elite athletes (archers). Paper 5 reports a valid and reliable method measuring periosteal cross sectional areas to accuracies of < 1% essential for identification of occupational activity and bone health measurement. NVs are useful metrics for assessing human performance and bone health. Morphometrics of bone health and NVs need to be optimised for validity and reliability in order to derive maximum performance and clinical benefit.

Declarations and Statements

1. I, Nicholas John Owen, 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, Nicholas John Owen, 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, Nicholas John Owen, 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: _____(candidate)

Date: *October 2018*

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Acknowledgements

This thesis represents the culmination of many years of work within the field of biomechanics. However, without the inspiration and support of Eben and Marie-Pierre it would have been possible. Thank you both. Thanks also to Dr Camilla Knight for acting as my advisor, and who is now an honorary biomechanist. Finally, thanks to Professor Jim Watkins for setting me on the correct path many years ago and for remaining a good friend and advisor since that time.

Si dubium mordeant

List of figure, tables and abbreviations

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List of abbreviations

3-D	three dimensional
B.C.	before the common era
BSP	body segment parameter
BW	body weight
CMJ	countermovement jump
CoG	centre of gravity
CT	computed tomography
FP	force platform
Fp	peak strength (IMTP)
fps	frames per second
GRF	ground reaction force
IMTP	isometric mid-thigh pull
MRI	magnetic resonance imaging
N1	Newton's 1st law of linear motion
N2	Newton's 2nd law of linear motion
N3	Newton's 3rd law of linear motion
P	mechanical power
PAP	postactivation potentiation
Pp	peak mechanical power of the whole body centre of gravity
RFD	rate of force development
S	strength
SI	Système Internationale d'Unités
Tp	pull initiation time for IMTP
VGRF	vertical component of the ground reaction force
WCoG	whole body centre of gravity
μCT	micro computed tomography
F100	force 100 ms after Tp in an IMTP
F250	force 250 ms after Tp in an IMTP
E	energy
W	work
d	distance
Y	school year
FCS	fairly complete skeletons
MRT	Mary Rose Trust
XSA	cross sectional area

List of published works to be submitted for PhD by publication

Paper 1

Effect of postativation potentiation on swimming starts in international sprint swimmers
Liam P. Kilduff, Dan J. Cunningham, Nick J. Owen, Daniel J. West, Richard M. Bracken and Christian J. Cook.
Journal of Strength and Conditioning Research. 2011. 25(9)/2418-2423

Applicant's input
Development of methods for data collection and analysis, namely:
- Data collection protocols and data analysis methods for assessment of power in a countermovement jump.
- Development of method for measuring ground reaction force and its vertical and horizontal components for a swimming start with a force plate mounted on the starting block.
- Development of a video based kinematics measuring system for the measurement of swimming start times to 15 metres

Data collection and analysis of data. Writing key elements of the methods section and elements of the introduction.

Paper 2

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players
Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075

Applicant's input
Development of methods for data collection and analysis, namely:
- Data collection protocols and data analysis methods for assessment of power in a countermovement jump.
- Development for the data collection of force-time characteristics for an isometric mid-thigh pull.
- Development of the method of analysis of the force-time characteristics of an isometric mid-thigh pull. Specifically, a reliable definition of time of initiation of the pull and methods for the determination of peak instantaneous rate of force development.

Data collection and analysis of data. Writing key elements of the methods section and elements of the introduction.

Paper 3

Development of a criterion method to determine peak mechanical power output in a countermovement jump
Nick J. Owen, James Watkins, Liam P. Kilduff, Huw R. Bevan and Mark A. Bennett.
Journal of Strength and Conditioning Research. 2014. 28(6)/1552-1558

Applicant's input
Development of methods for data collection and analysis, namely:
- Data collection protocols and data analysis methods for assessment of power in a countermovement jump.
- Development of methods of optimising key variables.
- Statistical analysis of resulting data.

Data collection and data analysis including statistical analysis. Writing the paper.

Paper 4

Normative data for lower limb peak mechanical power in children aged 7 to 11 years old
N.J. Owen, W. Griffiths & J. Watkins. Journal of Comorbidity 2015; 5: 93.

Applicant's input
- Development of all methodology including testing protocols.
- Statistical analysis
- Writing the paper

Paper 5

A computational method of obtaining reliable measurement of periosteal cross-sectional area of human radii from laser scans
P. Mahmoodi, S. Annan and N. Owen. Proceedings of the 23rd UK Conference of the Association for Computational Mechanics in Engineering 2015, Swansea. 73-76.

Applicant's input

- Development of original concept and principles of analysis
- Acquisition of resources
- Co-writing the paper
- Statistical analysis

Please see Appendix 1. for substantiating statements by co-authors for all papers. All co-authors had sight of this list.

Copies of the papers

Paper 1

Effect of postactivation potentiation on swimming starts in international sprint swimmers

Effect of Postactivation Potentiation on Swimming Starts in International Sprint Swimmers

Liam P. Kilduff,[1] Dan J. Cunningham,[1] Nick J. Owen,[1] Daniel J. West,[1] Richard M. Bracken,[1] and Christian J. Cook[2]

[1]Sport and Exercise Science Research Center, Swansea University, Swansea, United Kingdom; and [2]UKsport, Bath University, Bath, United Kingdom

Abstract

Kilduff, LP, Cunningham, DJ, Owen, NJ, West, DJ, Bracken, RM,

PVF: 1,462 ± 280 vs. 1,518 ± 311 N, $p = 0.038$); however, time to 15 m was the same when both starts were compared
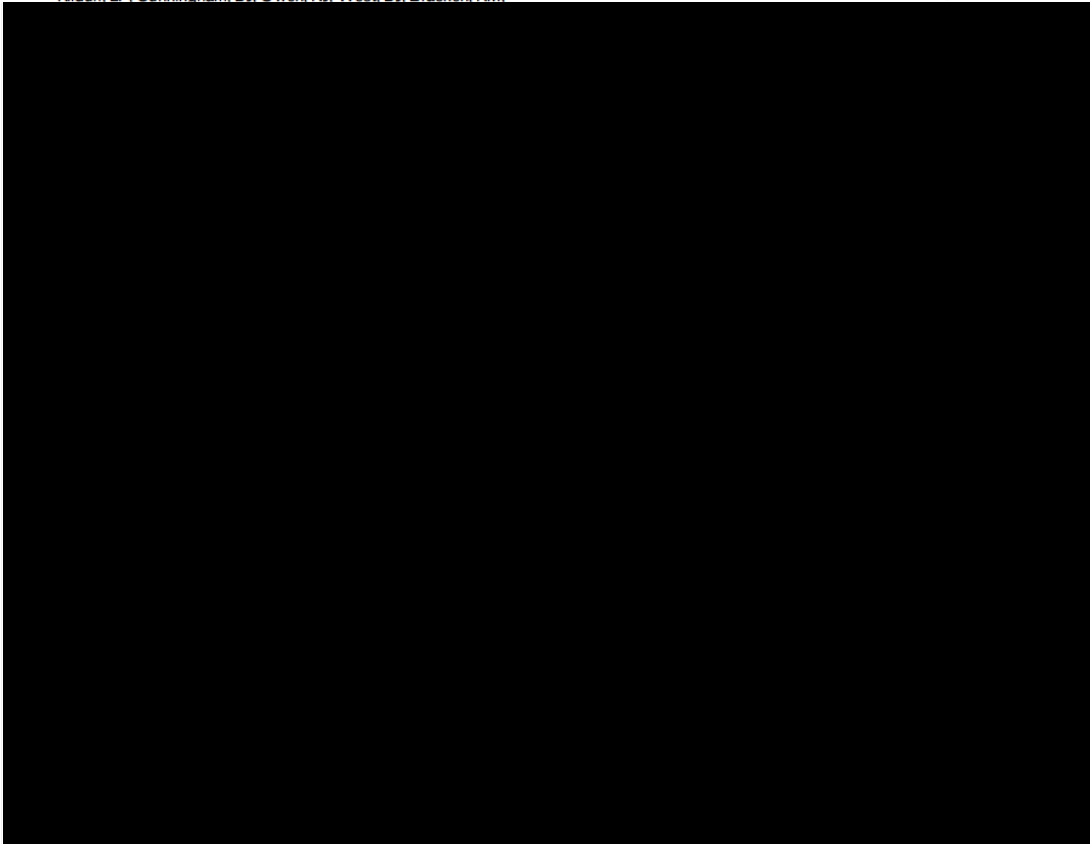
physiological condition, namely, postactivation potentiation
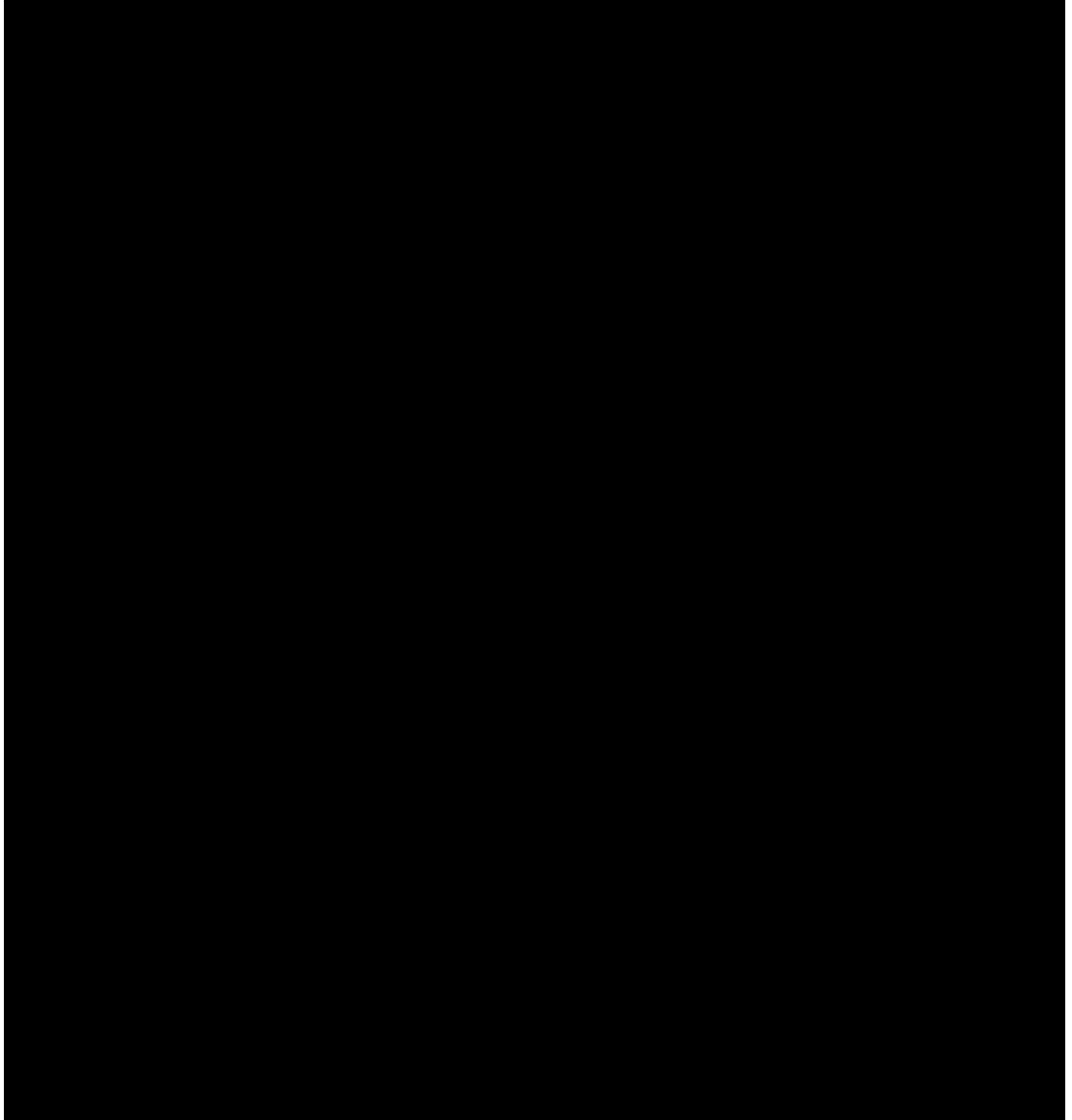
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(PAP), with PAP defined as an acute enhancement of muscle function after a PAP stimulus (13).

The literature regarding an athlete's ability to harness PAP

TABLE 1. Physical characteristics of subjects at

national record in their respective events. Swimmers trained

effect over the duration of the study (ES = 0.78, $p = 0.759$).

15

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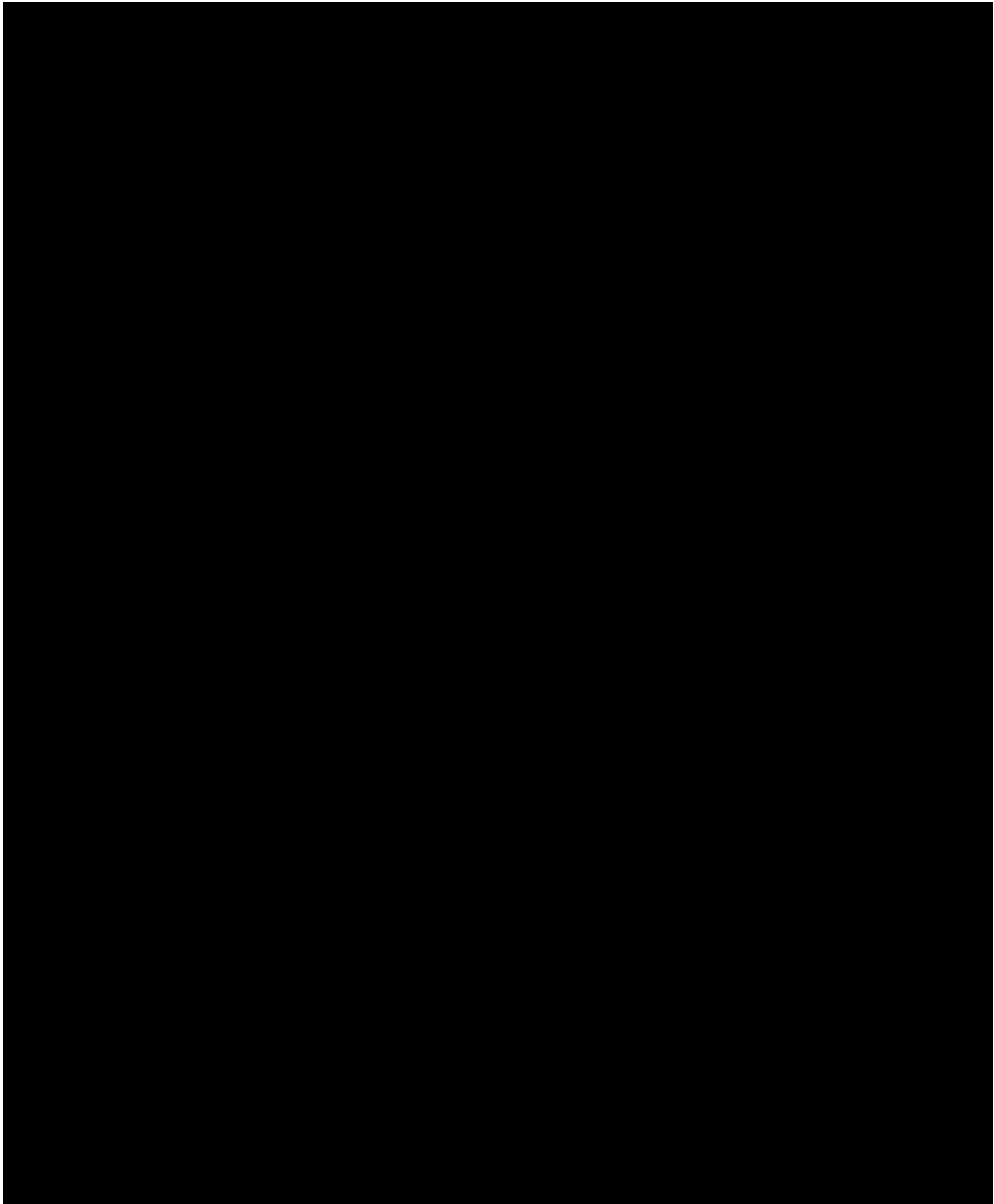
position, the subject was given verbal command 'take your mark,' and shortly after the starting signal was sounded. The
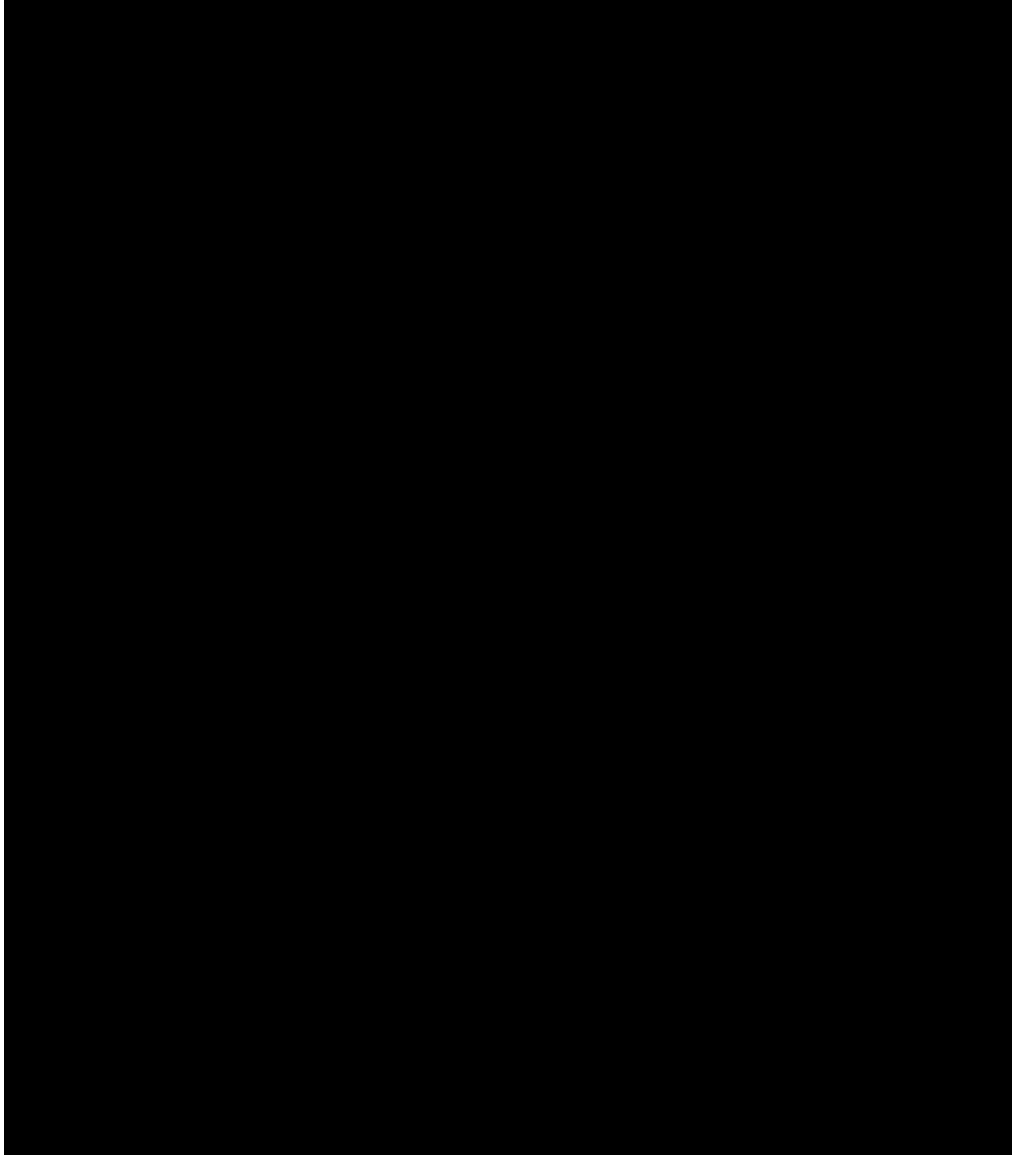
repeated measures 1-way ANOVA to determine whether PO,

17
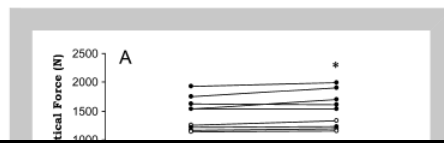
recovery from the preload stimulus, and this PO was significantly higher than the POs at all other time points (Figure 2A).

Jump Height

The repeated measures ANOVA revealed a significant time effect on JH ($F = 20.963$, $p < 0.001$). Maximum JH during the CMJ was observed after 8 minutes of recovery from the PAP
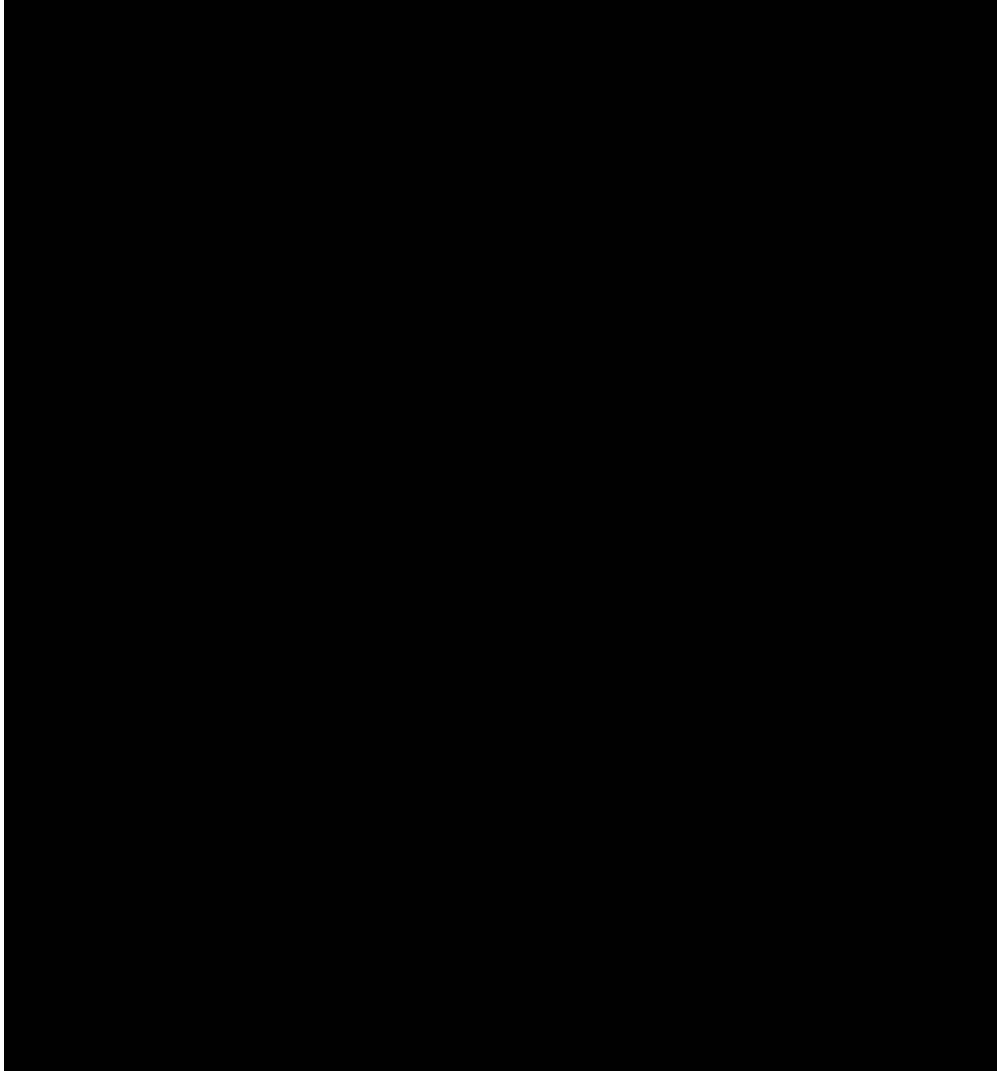
study produced their peak power output after 8 minutes of   up comprising of 1 set of 3 repetitions on the squat exercise lead

to a similar dive start time compared to the swimmers traditional

2. Baechle, TR and Earle, RW. Resistance training and spotting techniques. In: *Essentials of Strength Training and Conditioning*

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sprint swimmers. *J. Strength Cond. Res*, in press.

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Paper 2

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players

Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.

Relationships Between Force–Time Characteristics of the Isometric Midthigh Pull and Dynamic Performance in Professional Rugby League Players

Daniel J. West,[1] Nick J. Owen,[1] Marc R. Jones,[1] Richard M. Bracken,[1] Christian J. Cook,[2] Dan J. Cunningham,[1] David A. Shearer,[1] Charlotte V. Finn,[1] Robert U. Newton,[3] Blair T. Crewther,[4] and Liam P. Kilduff[1]

[1]Sports and Exercise Science, School of Engineering, Swansea University, Swansea, United Kingdom; [2]UKsport, Biomedical
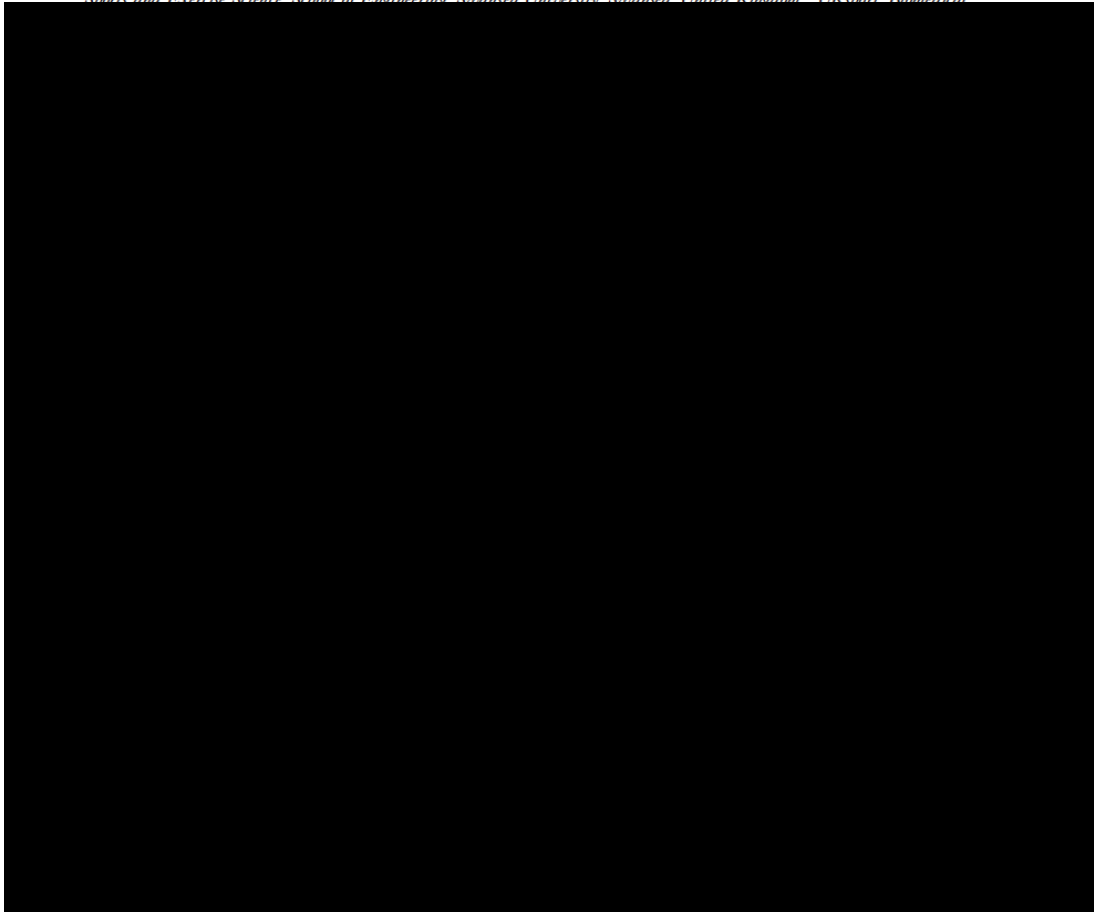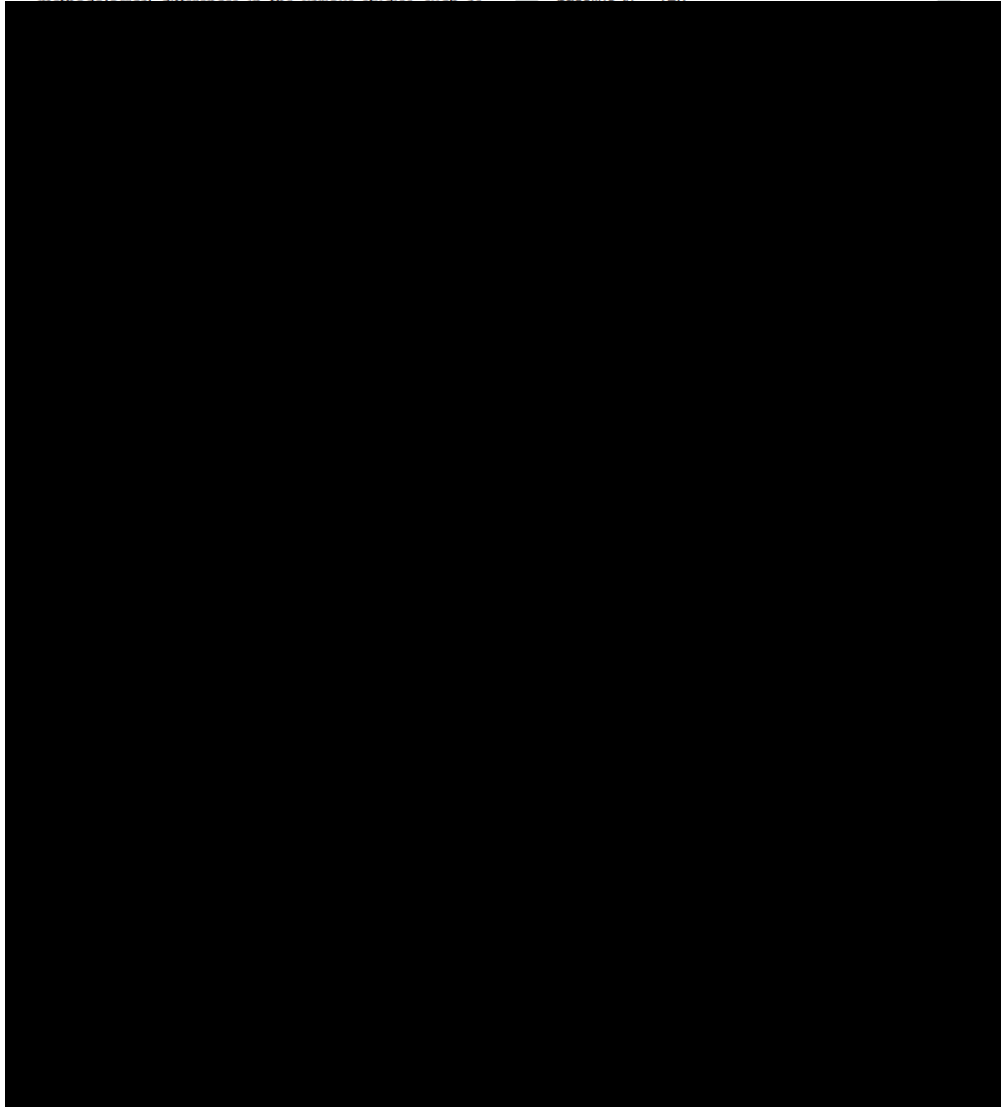
To date, there is no uniform agreement between researchers on the role isometric tests play in sports performance diagnosis with much of the discrepancies because of

TABLE 1. Physical characteristics of subjects at baseline ($n = 12$).*

The IMTP testing was carried out with players standing on a portable force platform (type 92866AA, Kistler Instruments

posttrigger phase and lasting for approximately 5 seconds. The platform's calibration was checked before and after

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each testing session. During each trial, subjects were instructed to pull as hard and as fast as possible for a period of approximately 5 seconds. These commands were based on previous research indicating that the use of these instructions

the trigger point. The start time (T_s) of the IMTP was then defined as the instant, after the trigger point, that the first derivative exceeded the mean value plus 5 SDs.
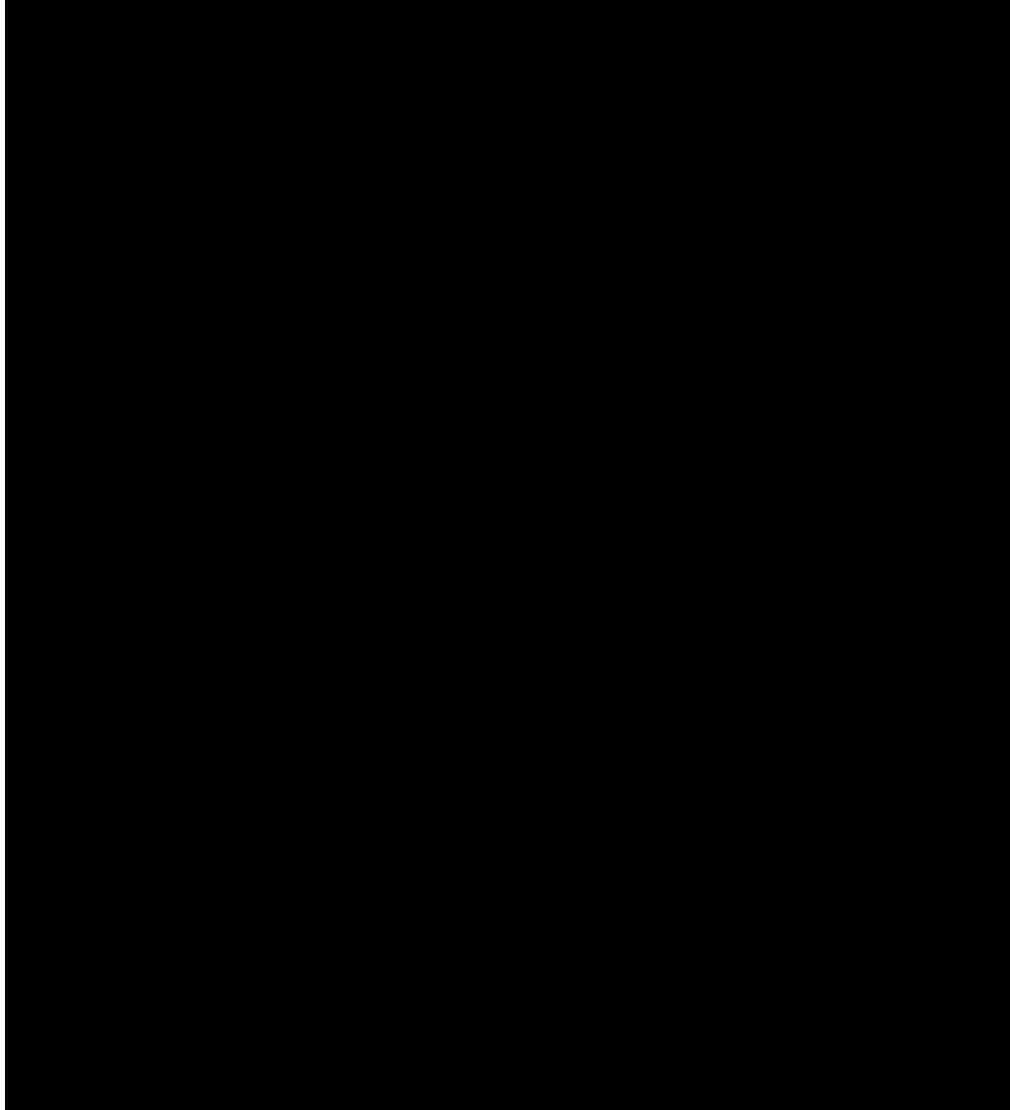
The PF was determined from the vertical component of the
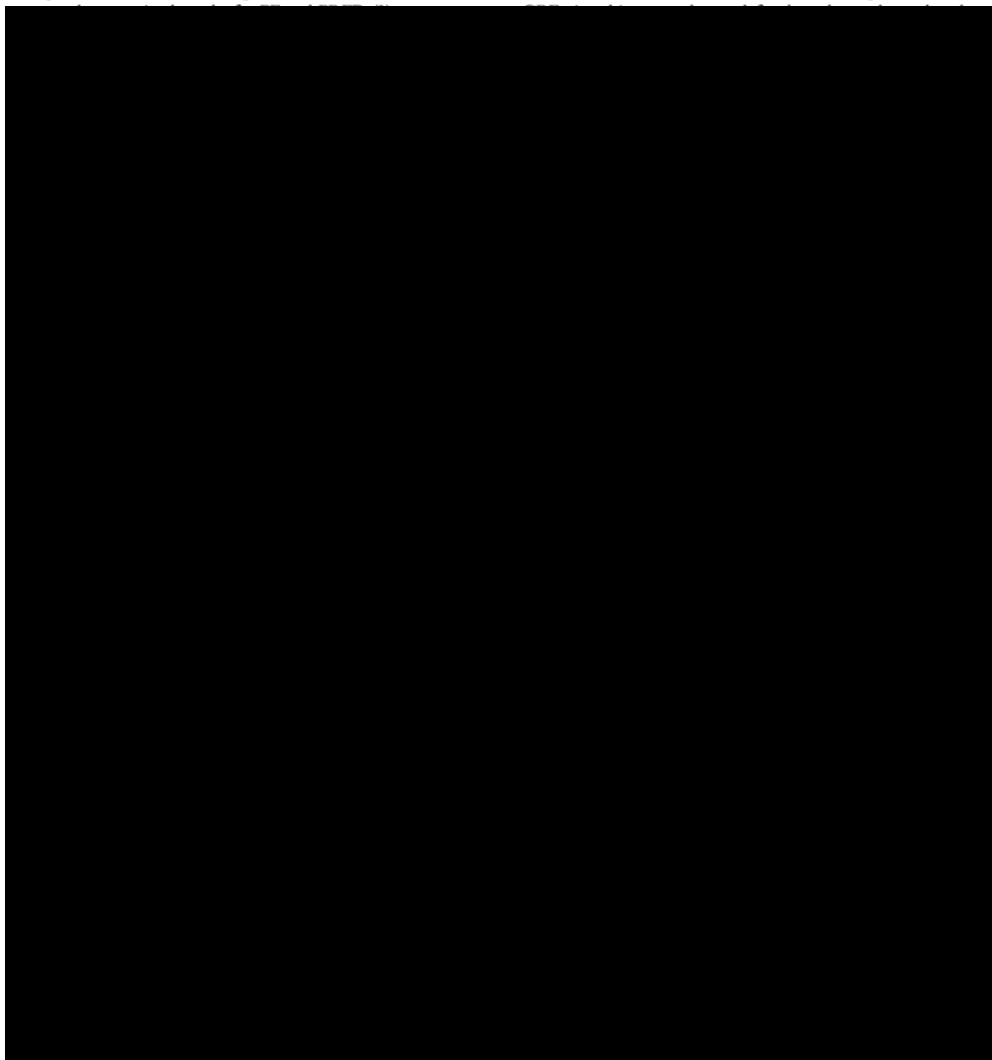
discarded to avoid the edge effects associated with digital filtering, and a mean and SD were calculated for the remaining 1 second of quiet standing immediately before

Instantaneous RFD was calculated from the first derivative of the vertical GRF. Before numerical differentiation, the vertical GRF was filtered using a dual-pass Butterworth filter

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TABLE 2. Relationships between various force measures, obtained during the IMTP and dynamic performance.*

(Table 2). In addition, PRFD

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power, respectively (Table 2). Relative F100ms was highly correlated to 10-m time and CMJ height (Table 2, Figure 1A, B).

DISCUSSION

researchers have based their conclusions on a limited sample size, and some studies reported findings from nonelite populations. In this study, we had a sample size of 39 elite rugby league players, which adds additional validity and application to the current findings. In addition, this article
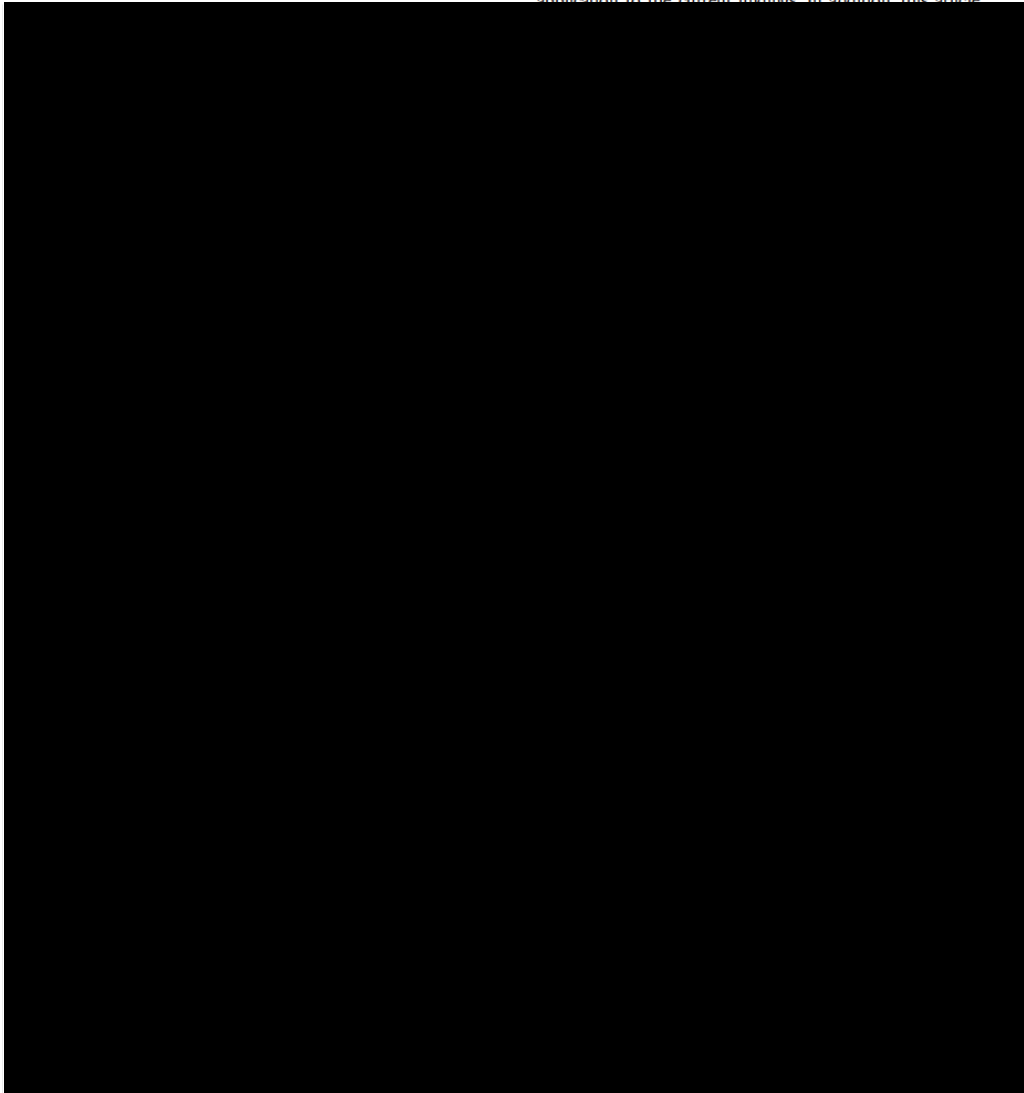
relation to dynamic sports. The majority of previous

isometric maximum strength in college wrestlers. *J Sports Sci Med* 1: 108–113, 2006.

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Paper 3

Development of a criterion method to determine peak mechanical power output in a countermovement jump

Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump

NICK J. OWEN,[1] JAMES WATKINS,[1] LIAM P. KILDUFF,[1] HUW R. BEVAN,[2] AND MARK A. BENNETT[3]

[1]Applied Sports Technology Exercise and Medicine Research Centre, College of Engineering, Swansea University, United Kingdom; [2]The England and Wales Cricket Board, London, United Kingdom; and [3]Ospreys Rugby, Liberty Stadium, Swansea, United Kingdom

ABSTRACT

Owen, NJ, Watkins, J, Kilduff, LP, Bevan, HR, and Bennett, MA.

INTRODUCTION

uscular power is widely considered to be a key
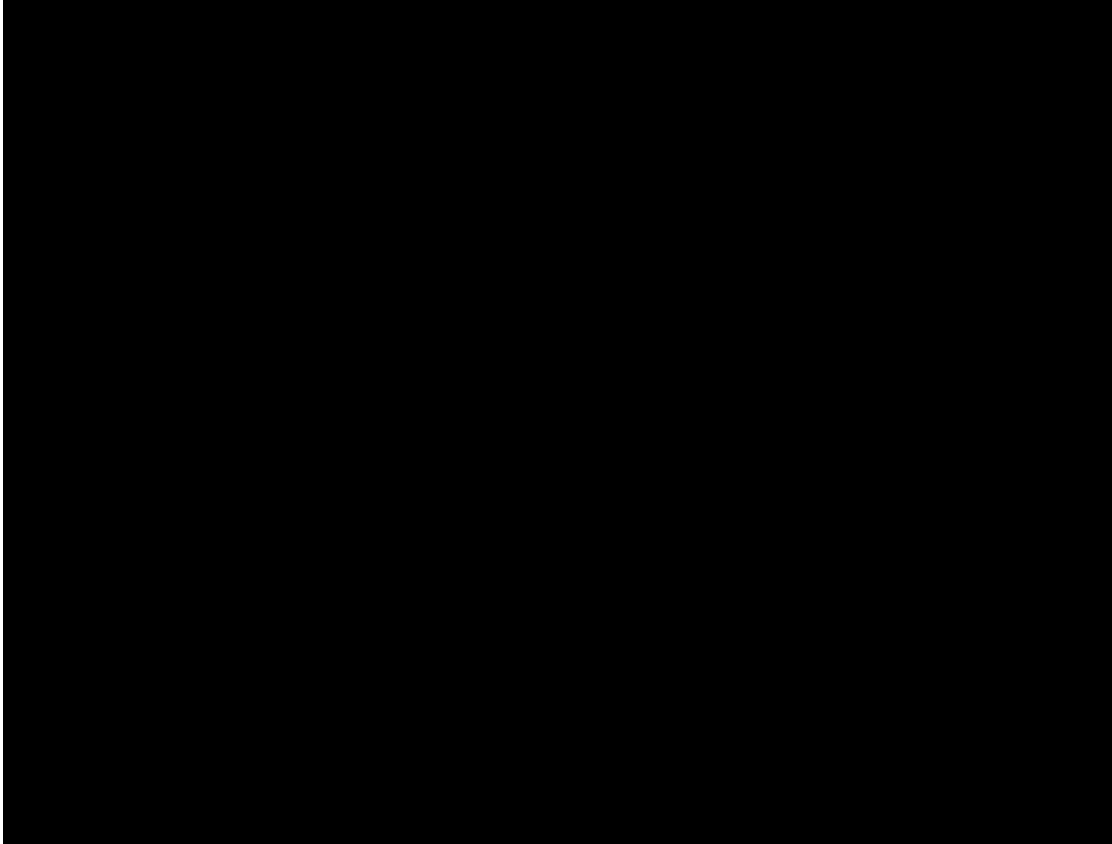
tion of all key variables. Consequently, no criterion protocol

4,000
3,500
3,000
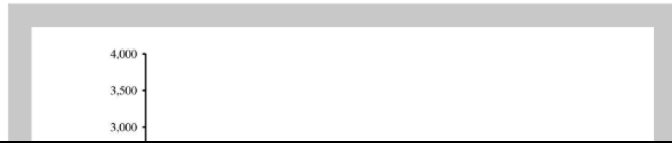
Body mass (BM) was determined from BW and taken to be $BW \cdot g^{-1}$ (kg) with g = acceleration due to gravity.

Subjects

The participants were 15 male
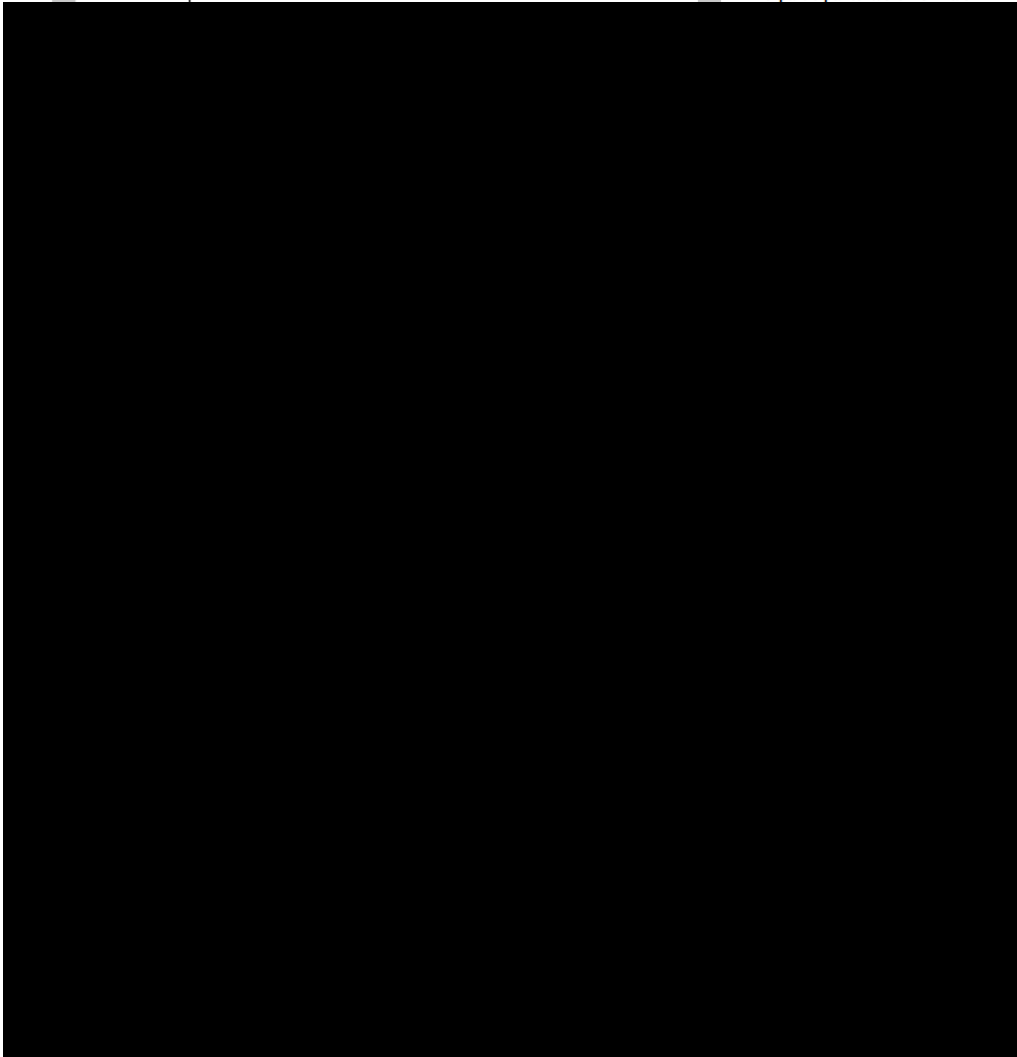
by BM to determine instantaneous velocity for time points

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TABLE 2. Mean and *SD* of body weights determined at different sampling frequencies during 1 second of quiet standing (*n* = 15).

LBPP from performance in a CMJ, force–time histories recorded for the vertical force range analysis were used. These 15 force–time histories were then resampled using Bioware's resampling function at 500 and 100 Hz. The LBPP was deter-

of the stance phase, will be in
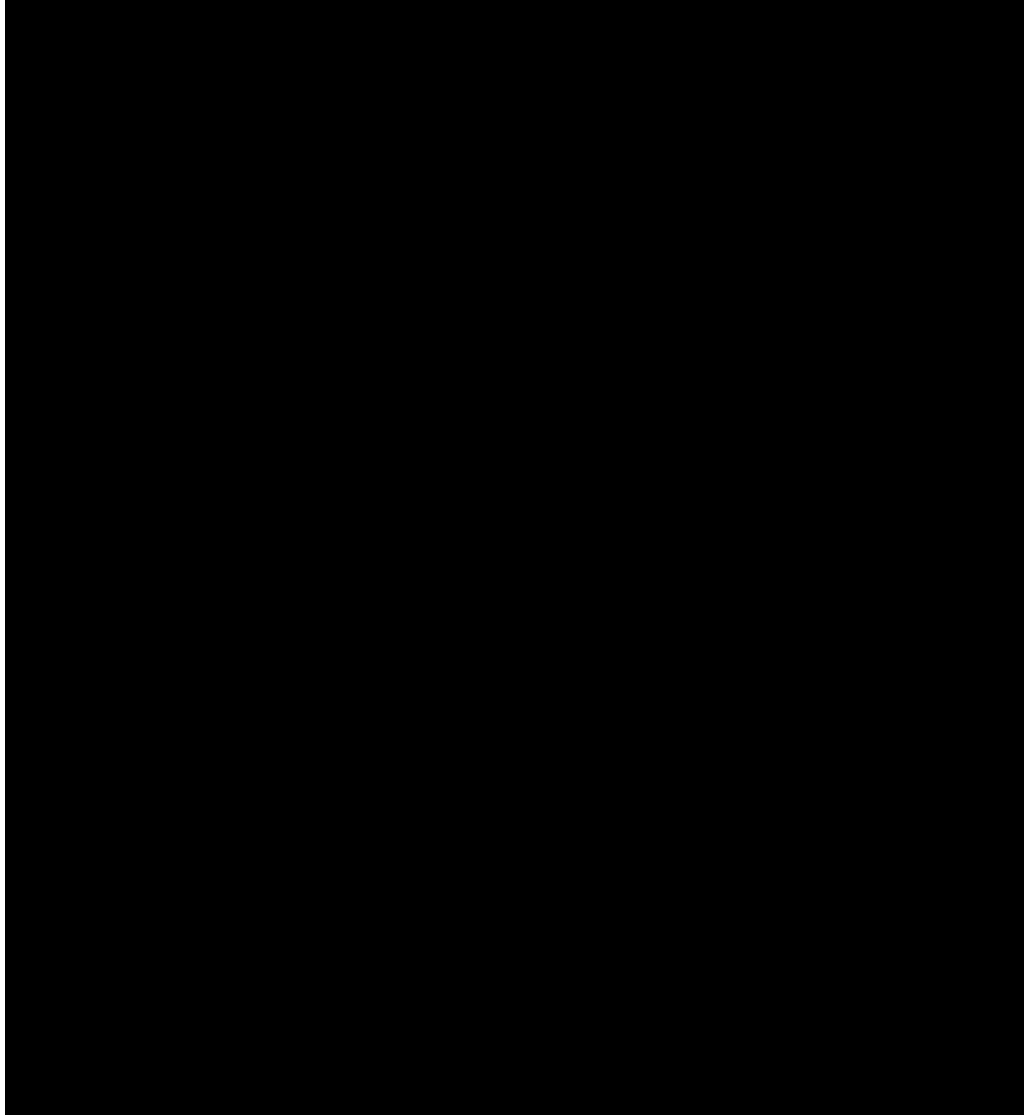
30
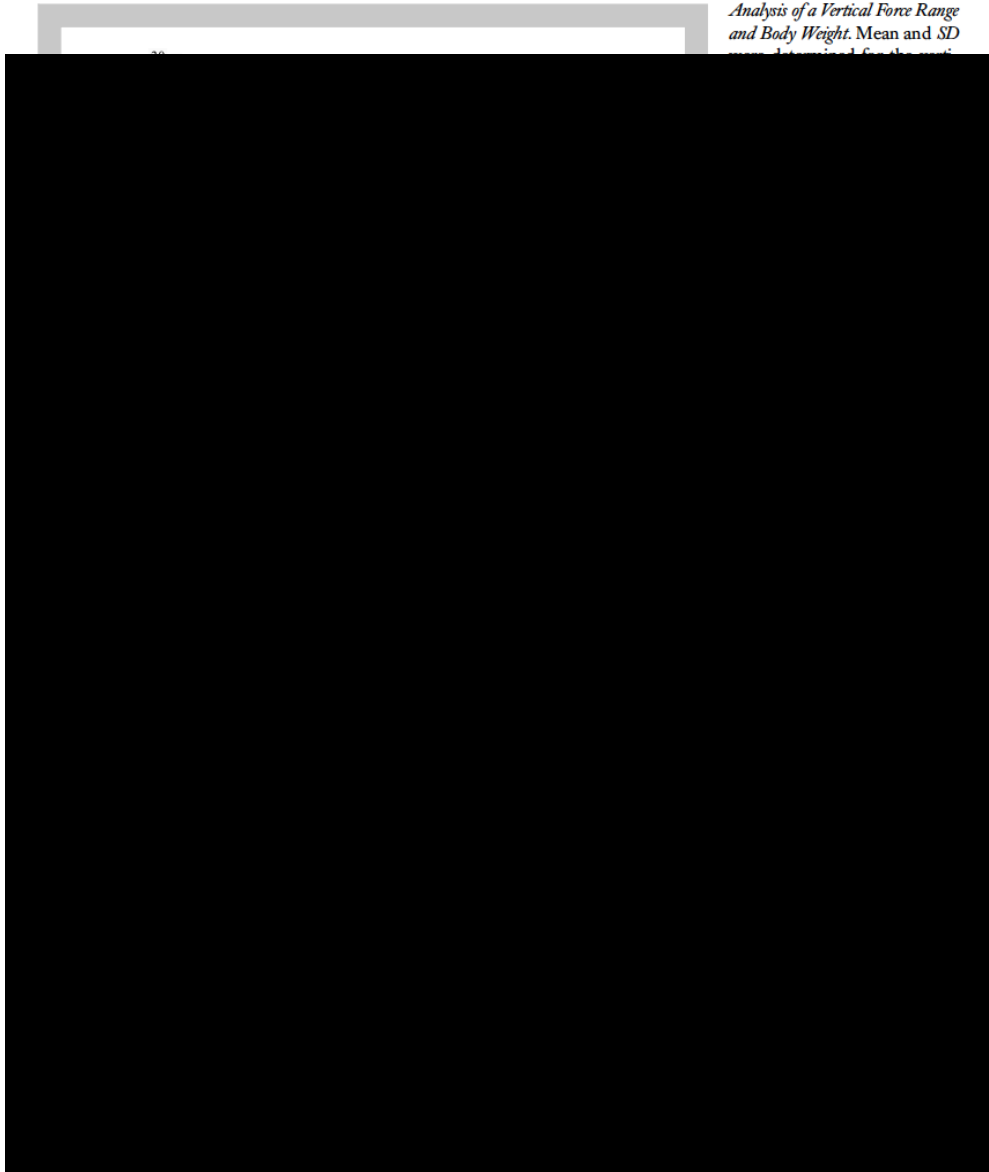
Figure 4. Graph of the rate of change of the *SD* of NPD.

Analysis of a Vertical Force Range and Body Weight. Mean and *SD* were determined for the verti...

...centage difference (NPD). For each time point, t_s = 90 ms through to t_s + 30 ms, mean

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moving up that is, a counter-movement before the CMJ, and half start by immediately dipping. Thus at the start of a CMJ, it is

†A specification of BW ± 5 SD as opposed to a reduction in BW for jump initiation was necessary because generally approximately half of all jumpers start a CMJ by first raising their centre of gravity.
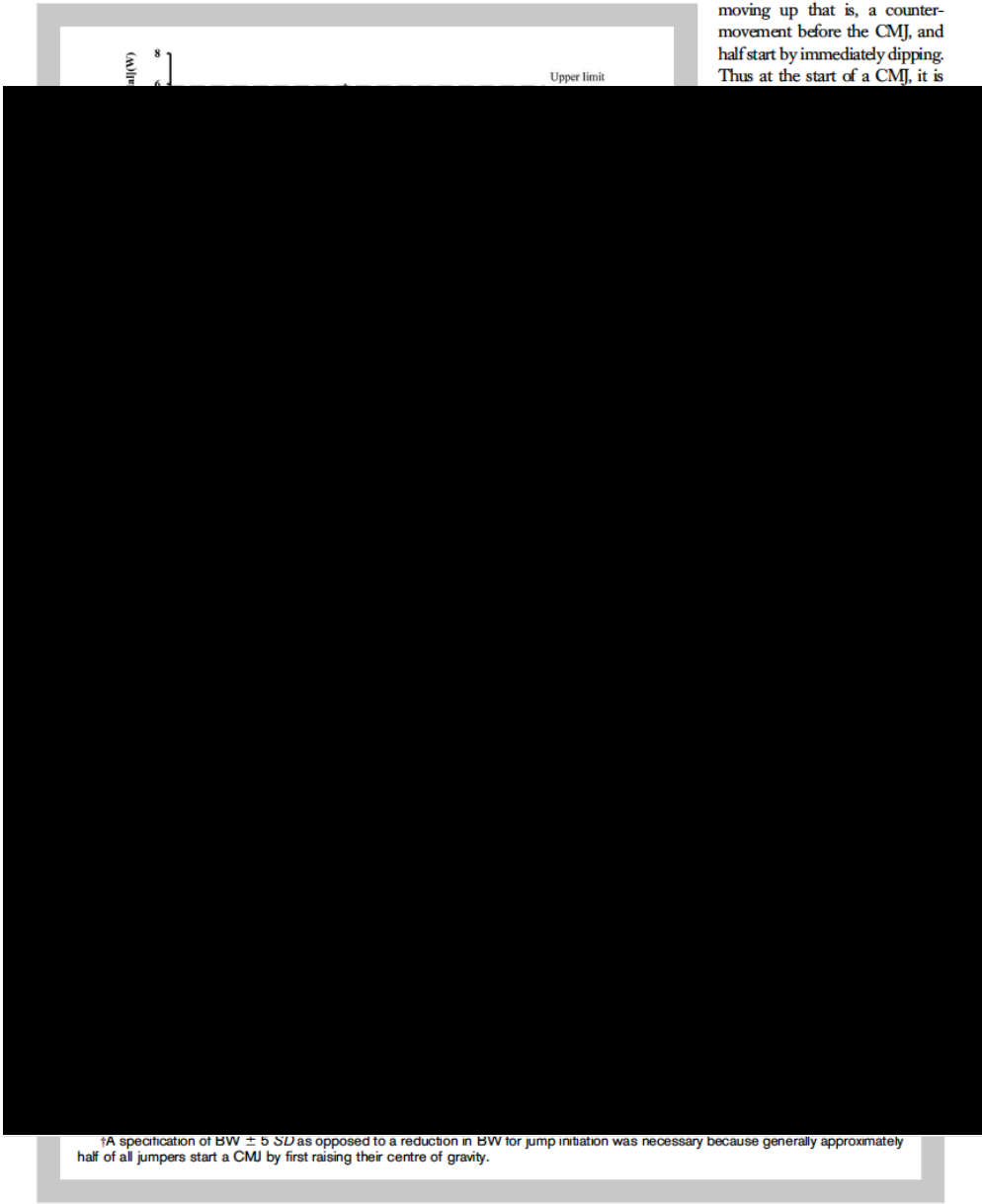
and trapezoidal rule value) is plotted on the x axis. The analysis resulted in a mean of the difference of 13 W and limits of agreement (mean $\pm$ 1.96 $\times$ SD) of 6 and 19 W.

of interest in this study was the force–time history of a CMJ. Usually, Fourier's analysis is used to determine the highest frequency present in a signal, however a force–time history cannot be represented by a function and is noncyclical and as
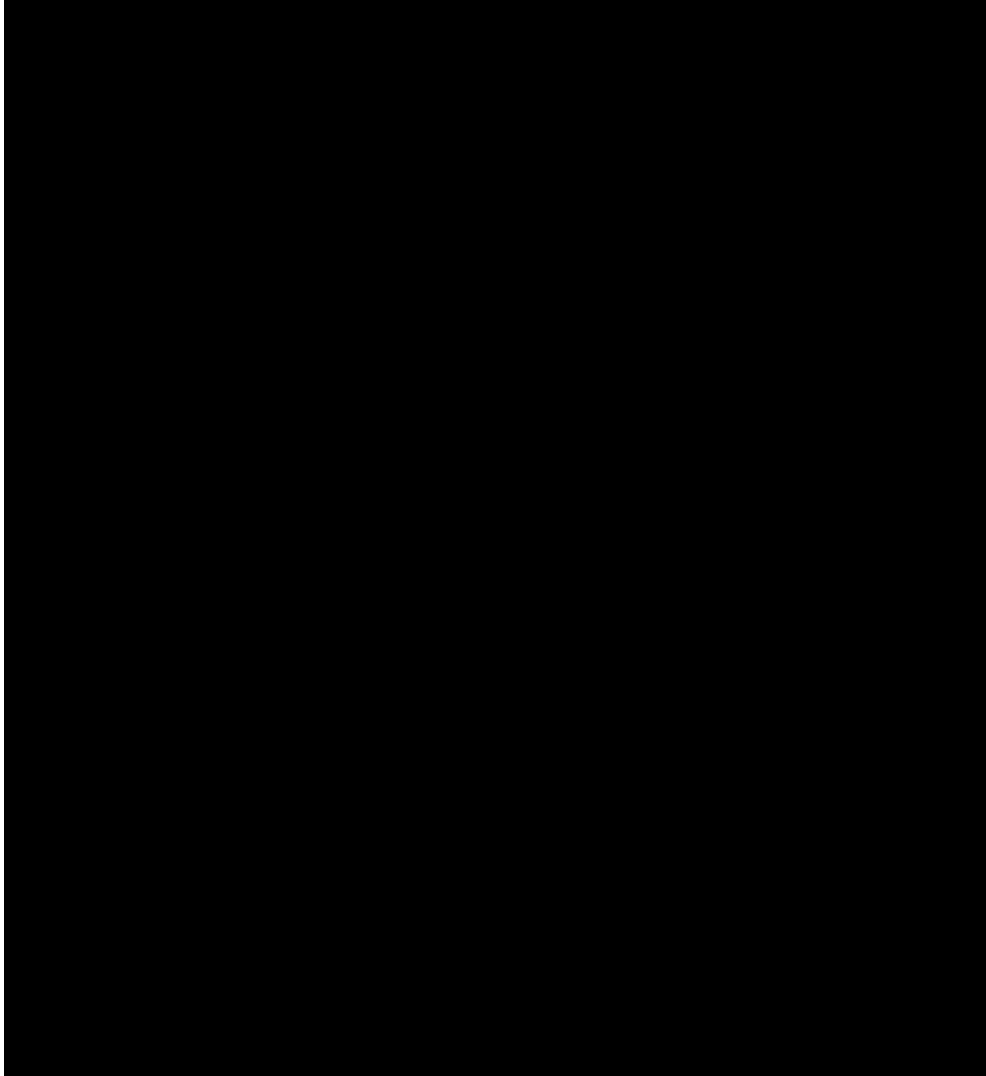
double the highest frequency contained in the signal is necessary to ensure that none of the original signal is lost during the sampling process and also to prevent aliasing. The signal

Figure 3 shows that the maximum error, ΔP, in the determination of peak power between Simpson's rule and the trapezoidal rule would be, $\Delta P \leq 0.13\%$ (confidence interval = 95%).

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However, because it is unclear which of these methods of integration gives the more correct result, the best estimate of the correct value of peak power can be taken as the mean

2. Bevan, HR, Owen, NJ, Cunningham, DJ, Kingsley, MIC, and Kilduff, LP. Complex training in professional rugby players: Influence of recovery time on upper-body power output. *J Strength*
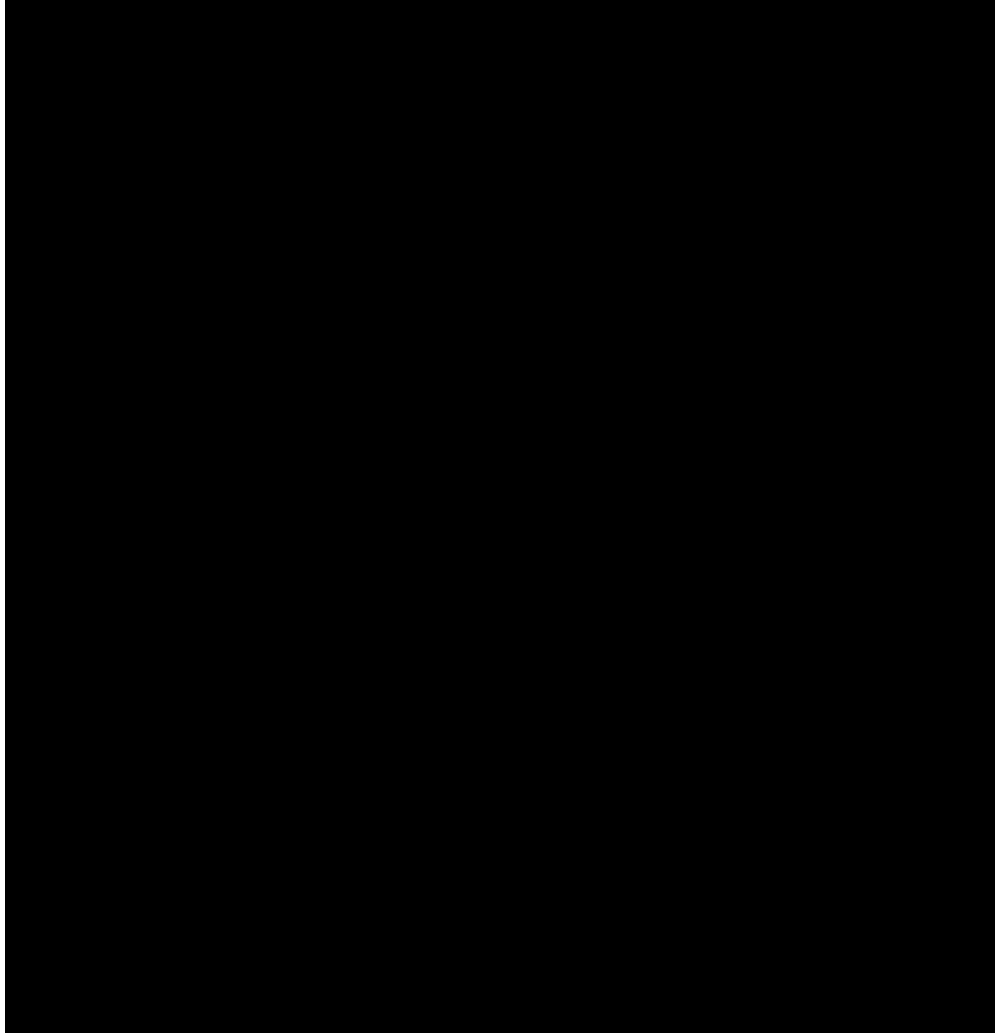
concentric), velocity, and jump spring stiffness.

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Paper 4

Normative data for lower limb peak mechanical power in children aged 7 to 11 years old

N.J. Owen, W. Griffiths & J. Watkins. Journal of Comorbidity 2015; 5: 93.

from similar research projects have indicated greater success in therapy when the children are actively involved in the therapeutic process and in determining the objectives of the treatment themselves and in cooperation with them.

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Missiuna, C. & Pollock, N. (2000). Perceived efficacy and goal setting in young children. *Canadian Journal of Occupational Therapy, 67,* 101–109.

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Keywords: Daily routines; "Make my day"; Evaluation; Young children.

Normative data for lower limb peak mechanical power in children aged 7 to 11 years old

N.J. Owen[1], W. Griffiths[2] & J. Watkins[1]
[1]*Applied Sports Technology, Exercise and Medicine Research Centre, Swansea University, Swansea, SA2 8PP, UK. n.j.owen@swansea.ac.uk;* [2]*Neath Port Talbot Education Authority, Civic Centre, Port Talbot, UK.*

Aim: There are currently about 45 published instruments for the assessment of motor development in children. However, all of the tests lack robust evidence of reliability and validity[1]. A high levels of lower limb peak muscular power (Pmp) is widely considered a key determinant of athletic performance[2]; conversely it is reasonable to assume that poor physical performance, characterised by poor coordination, would be associated with low levels of Pmp. However there are currently limited valid data on normative values of Pmp in children. The aim of this study was to report valid normative data for Pmp in children.

Method: Children 7 to 11 years old (n= 791, age 9.26 ± 1.20 decimal years, stature = 1.338 ± 0.094 m, body mass = 34.7 ± 9.7 kg) of mixed gender were randomly selected from schools in South Wales. Each child performed one countermovement jump (CMJ) off a force platform with their hand held on their hips to isolate the lower limbs. The ground reaction force was recorded and the momentum impulse principle was used to derive a criterion measure of lower limb peak instantaneous power (Pp)3. A pilot study had shown good reliability for Pp in children in this age range (ICC > 0.92). Participants were grouped in school years (Y) and comparisons were made between genders and year groups for Pp.

Results: There was no significant difference in Pp between genders for year group (p = 0.05). Combined gender groups for each school year produced Pp that were normally distributed and had the following values (mean Pp, standard deviation), Y3 = 905 ± 191 W, Y4 = 1047 ± 233 W, Y5 = 1230 ± 258 W, Y6 = 1367 ± 326 W. A significant difference in Pp was found between successive mixed gender year groups (p= 0.01). Y3 (n= 190) to Y4 (n = 182), t = 6.01, p < 0.001, Y4 to Y5 (n = 215), t = 7.67, p < 0.001, Y5 to Y6 (n = 204), t = 3.94, p < 0.001.

Discussion: This study indicates that Pp produced in a single-trial CMJ has the potential to provide information on the coordination of children aged 7 – 11 years, with a high level of discrimination. For example, in Y3 (aged 7-8 years) there is a 12% increase in Pp between the 5th and 10th percentile. Pp as measured in a CMJ has the potential to augment tests like Movement Assessment Battery for Children-2. However more study is needed regarding the potential benefits of allometric scaling of Pp and further splitting school year groups into 3 month groups and comparison with other tests of physical ability.

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3. 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.

Keywords: Power; Coordination; Vertical jumping; Children; Force platform.

Specificity of motor abnormalities in DCD in the following children with Autism Spectrum Disorder using a standardized neuro-psychomotor assessment

A. Paquet[1,3,4], B. Olliac[4,5], B. Golse[2,3,6] & L. Vaivre-Douret[2,6,7]
[1]*Department of Psychology, University of Paris Descartes, Sorbonne Paris City 75006, Paris. France aude.paquet@etu.parisdescartes.fr;* [2]*Department of Medicine, University of Paris Descartes, Sorbonne Paris City, Paris, France;* [3]*INSERM, UMR 1178, University of Paris Sud and Paris Descartes, Paris, France;* [4]*University Pole of Psychiatry of the Child and the Teenager, Limoges, France;* [5]*UMR 1094, University of Limoges, Limoges, France;* [6]*Department of Child Psychiatry, AP-HP Necker-Enfants Malades University Hospital, IMAGINE affiliation, Paris, France;* [7]*Department of Pediatrics, AP-HP Paris Center Port Royal-Cochin Hospital, Paris, France.*

Aim: Decreased motor performance was described in Autism Spectrum Disorders (ASD) with a disturbance in walking, posture, coordination or arm movements. There is evidence in favour of comorbidity between Developmental Coordination Disorder (DCD) and ASD, including impairment of voluntary actions or locomotion. Never the less some individuals with ASD show no decrease of the driving performance. Although there are difficulties in defining the DCD in the studies in children with ASD, it is estimated that there is a high prevalence of classic motor symptoms of DCD in these children. Objective: To highlight the semiology of movement disorders among children with ASD, using a neurodevelopmental assessment tool.

Method: Thirty-five children with ASD are recruited in a child psychiatry service (Limoges) and Autism Resource Centers (Bordeaux, Limoges, Toulouse). Evaluations of the first instances (psychiatric/ ADI; psychological/ KABC-II/ Rey's figure/ London tower; understanding/NEEL; psychomotor/ M-ABC) were supplemented by a standardized assessment battery of neuro-developmental psychomotor functions (NP-MOT).

Results: From the NP-MOT test, the tests of two-hand and finger praxis are largely failed(33% and 60%). Manual and digital gnosopraxis are deficient (72% and 65%). Postural deficit was found in both the static equilibrium tests (60%) and dynamic (53%). There is also the difficulties of coordination between the upper and lower limbs in 55% of children. We find a failure to the M-ABC (79%). Spatial orientation is deficient in 47% and visuospatial structuring in 56% of cases. Children with Asperger's Syndrome (AS) were better on perceptual–visuo-spatial tests.

Discussion: We can emphasize in the light of the results of manual and digital gnosopraxis tests a planning deficit in children with autism. A gesture programming deficit is also highlighted by the poor results in the tests of two-hand praxis NP-MOT, by failure to M-ABC tests despite the training of the child and by the visuospatial test. These planning and programming difficulties gesture increase a mixed type of dyspraxia (ideomotor/visiospatial and constructive) of this DCD in children with ASD. However it appears that children with AS have a better overall motor coordination and we did not notice any perceptual and visuospatial disorder in these children. And children with AS would present a particular type of ideomotor typology of DCD. The use of neurodevelopmental tool allows to refine the semiology of motor abnormalities in the DCD.

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Keywords: Autism Spectrum Disorders; Motor skills; Neuro-psychomotor functions; Developmental Coordination Disorder.

Paper 5

A computational method of obtaining reliable measurement of periosteal cross-sectional area of human radii from laser scans

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A computational method of obtaining reliable measurement of periosteal cross-sectional area of human radii from laser scans

P. Mahmoodi, S. Annan and *N. Owen

College of Engineering, Swansea University, Singleton Park, Swansea, SA2 8PP

*n.j.owen@swansea.ac.uk

ABSTRACT

The accurate quantification of bones cross-sectional geometry provides valuable information about mechanical properties of bones such as rigidity to torsional, bending and compressive loading and also reveals insights into habitual activities of humans in the past. However, the use of current methods can produce large errors between measured and true cross-sectional areas. In this study the minimum cross sectional area was calculated at mid-shaft for a unique collection of laser scanned radii bones, recovered from Mary Rose warship, using a novel technique. A computational method was used to measure multiple cross-sectional areas for different orientations to then determine a minimum. This was then taken to represent a reliable mid-shaft cross-sectional area. The reliability of the process was tested using Bland and Altman plots to analyse the agreement between measurement trials. The systematic bias between the two measurement trials was $0.06mm^2$ (0.04% of the average cross-sectional area measurement) with 95% limits of agreement of $1.69mm^2$ (1.13%) and $-1.57mm^2$ (1.05%). Consequently this method can be used as a reliable measure of periosteal cross-sectional area. The possibility also exists to transfer the methods described here to other imaging technologies for example, micro CT and magnetic resonance imaging. This would augment existing methods of computational analysis and produce accurate models.

Keywords: computational modelling, bone topology, osteology, biomechanics

Introduction

The study of osteology and bone morphology refers to the detailed analysis of the form and structure of bone. The results of such analyses in human studies help science understand important areas of human development and health, such as habitual activities of humans in the past and evolutionary medicine [1,2]. The use of engineering theory, specifically beam analysis is increasingly used to analysis bones structurally. Recently the trend has been to use virtual bones derived from different imaging technologies for such studies [1]. The most common technologies used for creating dimensionally accurate virtual bones are laser scans [1], peripheral qualitative computed technology scan [2] and computed tomography scans [3]. However bones, when compared to manufactured objects, present certain challenges with regard to valid and reliable metrology. For example, it is common practice to align bones or limbs to be scanned with an external reference plane. Whilst this would provide a reliable position for repeated measurements of the same bone or limb, it would not necessarily allow reliable measurements of different bones due to inter-specimen/limb variation, that is, the same bone from different people vary considerably in shape and size. Consequently, the purpose of the current study is to develop a reliable method of measuring bone morphology, specifically mid-shaft cross-sectional area.

Materials and Methods

Human radii bones (n = 10), recovered from Mary Rose warship provided by the Mary Rose Trust, were used in this study

All radii were scanned on a FARO three dimensional (3-D) laser scanner (7 axis, 10 foot Fusion model; FARO Technologies Inc., Florida, USA). MeshLab (v1.3.1; Visual Computing Lab, Pisa, Italy) was used toinput into MATLAB.

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The minimum cross-sectional areas (at mid-shaft) of scanned bones, with arbitrary orientations, were measured in three steps. Reference bony landmarks were first defined from which orthogonal reference axis lines were determined. In the second step all the bones' reference axes were rotated to align them with the global reference frame. In the last step a computational method was used to find the minimum cross sectional area of the bone at the mid-shaft position.

Three reference bony landmarks were used to align the bones with the global reference frame to enhanced the performance of the method. Figure 1 shows the location of the bony landmarks used to define the reference axes, they were: a) the furthest point of the styloid process (point 1), b) the centre of the concaved surface on the proximal radial head (point 2) and c) the mid-point between the corners of the distal articulating surface above the ulnar notch and point 1 (point 3) . Orthogonal axes, $\vec{V}_{31}$ and $\vec{V}_{32}$, were then defined based on the coordinates of the bony landmarks. The desired orientation of bones was defined such that a vector connecting points 3 and 2 $\left(\vec{V}_{32}\right)$ is parallel to the global x-axis and $\vec{V}_{31}$ is located on a plane parallel to (x-y), Figure 1. The procedure of alignment of bones to the desire orientation consists of three stages. In the first stage the point cloud rotates about the y-axis by the angle of θ . Stage two involved rotation of the point cloud about
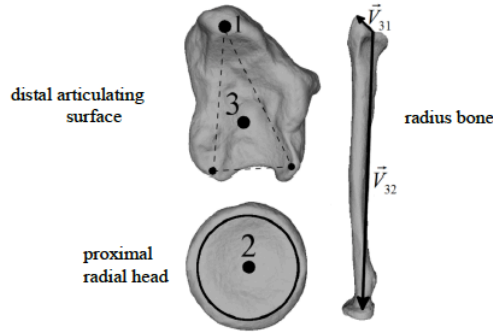
Figure 1: Position of reference bony landmarks and reference axes for each radius bone.

the z-axis by the angle of ϕ so that $\vec{V}_{32}$ became parallel to the x-axis Figure 2. In the final stage new coordinates of the scanned bone rotate about its longitudinal vector ($\vec{V}_{32}$) by the angle of ψ so that $\vec{V}_{31}$ is located on a plane parallel to (x-y) Figure 2. Thus, the point cloud at each stage is given by:

$$\begin{bmatrix} x_\theta \\ x_\varphi \\ x_\psi \end{bmatrix} = \begin{bmatrix} x_1 + l_\theta \cos\left(\theta - \theta^*\right) \\ x_1 + l_\varphi \cos\left(\varphi - \varphi^*\right) \\ x_\varphi \end{bmatrix}, \quad \begin{bmatrix} y_\theta \\ y_\phi \\ y_\psi \end{bmatrix} = \begin{bmatrix} y_{initial} \\ y_1 + l_\phi \sin\left(\phi - \phi^*\right) \\ y_1 + l_\psi \cos\left(\psi - \psi^*\right) \end{bmatrix}, \quad \begin{bmatrix} z_\theta \\ z_\phi \\ z_\psi \end{bmatrix} = \begin{bmatrix} z_1 + l_\theta \sin\left(\theta - \theta^*\right) \\ z_\theta \\ z_1 + l_\psi \sin\left(\psi - \psi^*\right) \end{bmatrix}$$

Where l_θ, l_ϕ and l_ψ are the length of the projection of vectors connecting a point on the point cloud to the point3 on planes (x-z), (x-y) and (y-z) respectively at each stage. The angles θ^*, ϕ^* and ψ^* are the initial angles between the projections of $\vec{V}_{32}$ on reference planes and axes.

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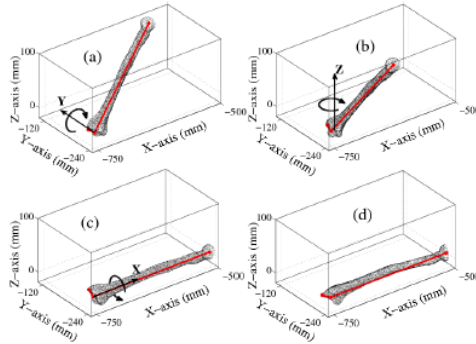
Figure 2: Rotation of the bone point cloud. a, b and c show the rotation of the bone with respect to y-axis, z-axis and x-axis or longitudinal reference line respectively. Final orientation of the bone is described in d.

In order to find a minimum cross-sectional area, an initial cross section is defined as the intersection of a plane parallel to (y-z) plane (local plane), Figure 3, and the bone at mid-point of the longitudinal
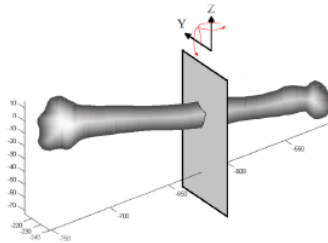
Figure 3. Local plane (y-z) used to define cross-sectional areas for different orientations

reference axes. In the second step a local coordinate system is defined such that its origin is located on the centre point of the initial cross section and its axes are parallel to the global coordinate system. In the next step, the minimum cross section area is determined by rotating the bone about the local y-axis and z-axis ($\pm 20^0$, 1^0 steps) and measuring the intersection of the bone and the local coordinate system at each orientation, thus producing 1600 cross-section measurements. The minimum cross-sectional area was then chosen. The minimum cross-sectional area of each bone was measured twice with measurements derived from separate laser scans. The pairs of measurements were then statistically assess for agreement.

Statistical Analysis

The aim of the statistical analysis was to assess reliability (repeatability) of the method of measuring mid-shaft cross-sectional area. The test described by Band and Altman [5], measures the systematic bias between paired measurements of the same object and quantifies the 95% confidence limits of agreement (LOA).

Results

The systematic bias between the paired measurements was 0.06 mm^2 with an upper LOA of

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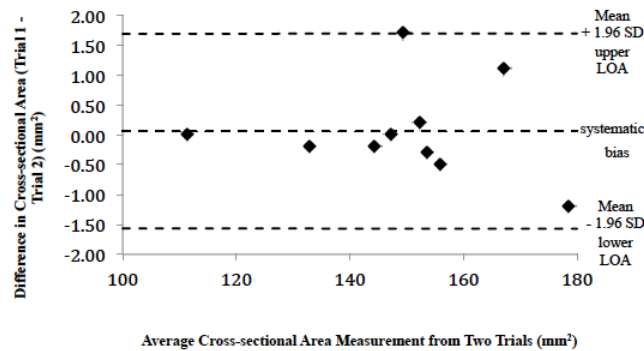
Figure 4. Bland and Altman plot of mid-shaft cross-sectional area

+1.69 mm^2 and a lower LOA of -1.57 mm^2, representing 0.04%, 1.13% and -1.05%, respectively, of the average cross-sectional area.

Conclusion and Discussion

The results of the study indicate that this method of assessing periosteal cross-sectional areas produces reliable and valid measurements within the range of the LOA. Analysis of bones for the assessment of occupational activity in humans increasingly uses engineering theory, specifically beam analysis. The current study provides quick and reliable method of providing metrics for such analyses. Future studies should increase the n number and determine the optimal orientation step and fan angle. Also, adaptation of this method for micro computed tomography and magnetic resonance imaging should be investigated, thus augmenting existing methodologies [6].

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Critical review

1 Introduction

The following introduction is intended to provide an overview of the areas that are important for this corpus. It is neither intended to be comprehensive nor complete, but to provide a background and historical context to the papers included herein. As such, it will demonstrate the linking themes between studies.

1.1 A selected brief historical overview of biomechanics

Biomechanics is the study of the structure and function of biological systems by means of the methods of mechanics (Hatze, 1974). Clinical and sports biomechanics refer to applying mechanical principles to human subjects and can trace its roots to the ancient Egyptians in as much as they are considered to be the originators of anatomical investigation (Cave, 1950; Elhadi et al., 2012). Cave (1950) considered their interest in anatomy as limited to that which was necessary to embalm individuals, as opposed to a curiosity about the function or structure of the human body. However, more recent research has determined that as long ago as 3100 before the common era (B.C.), Egyptian physicians had an interest in and knowledge of medicine and anatomy. For example, two works titled Practical Medicine and Anatomical Book were written by Dier or Athothis around 300 B.C.. These works may be the first practical and systematic studies of human anatomy (Elhadi et al., 2012).

Nevertheless, it was not until several centuries B.C. that the Greek philosophers started considering the mechanisms behind human function and movement (Cooper, 1983). Galileo Galilie (1560 – 1642) and Sir Issac Newton (1642-1727) both provided the foundations of modern dynamics (Cooper, 1983). Galileo, through his work on falling bodies and Newton through his establishment of his laws relating to motion (I. Newton, 1687).

In terms of modern biomechanics, the studies by Giovanni Borelli's (1608 - 1679), a student of Galileo, of human movement are normally considered to be the first in the field (Maquet, 1989; Pope, 2005; Thurston, 1999). His studies demonstrated a clear understanding of both anatomy and mechanics of movement (Figure 1). Figure 1. clearly illustrate Borelli's understanding of several key principles of biomechanics through a series of individual figures. For example, Borelli's *Fig* 3, illustrates

functional muscle mechanics in terms of lower leg extension and Borelli's *Fig* 5, illustrates the principle of balance and the line of gravity remaining within the base support. However, although Borelli was able to relate muscular movement to mechanical principles, he lacked the experimental tools to investigate his keen observations and, as such, he is considered one of the theoreticians (Cooper, 1983).
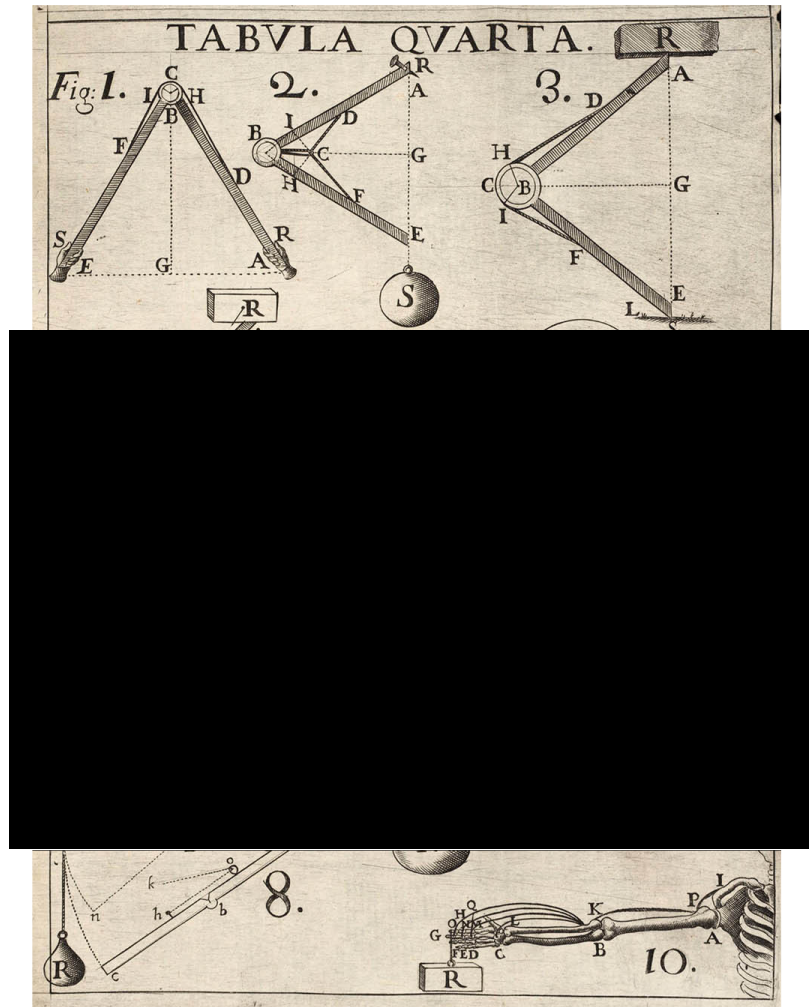
Figure 1. A plate from Giovanni Borelli's *De Motu Animalium* (1680)

1.1.1 Kinematics

Kinematics is the study of motion based on position (spatial) and time (temporal) data, without recourse to the cause of the motion (Watkins, 2014). In terms of experimental kinematics, the Weber brothers, Eduard (1806-1871) and Heinrich (1795-1878) were considered to be the first to record experimental locomotive data based on both observation and some basic measurements (Thurston, 1999). However, Eadweard Muybridge (1830-1904) was the first to use the concept of successive photographic images, and a scaled backdrop, to study the locomotion of horses (1878 Figure 2).

Figure 2. Eadweard Muybridge's *The Horse in Motion* (Library of Congress, Prints & Photographic Division [reproduction number LC-DIG-PPMSCA-06607])

In signal processing, periodic sampling is the process of representing a continuous signal with a sequence of discrete data values (Lyons, 2011). Consequently, if the motion of the horse in Muybridge's images is the signal and the photographic images are discrete data values, his study can be considered to be an early example of periodic sampling of physical activity and certainly a very early, if not the first, example of modern experimental work in kinematics.

Contemporary methods of collecting kinematic data include, but are not limited to, goniometers, linear position transducers, rotary position transducer, but the most common instrument is the high speed imaging system e.g. video cameras, that are able to collect successive images at equal time intervals. The number of images recorded a second is referred to as the frame rate or sample rate, having units of frames per second (fps) or frequency, hertz (Hz). Imaging systems are used to collect linear and angular kinematic data and can be used with a calibrated plane of interest or at fixed intervals of known position. Such systems can be used independently of, and in conjunction with kinetic measurement systems.

Current examples of kinematic imaging systems are Quintic Biomechanics ("Quintic Biomechanics," n.d.) and VICON (VICON, n.d.) . Quintic Biomechanics represents a typical video based system, using conventional video images to generate data. VICON though, does not use video as its prime data source but uses video cameras to determine the position of markers in 3 dimensional space, based on the principle of geometric triangulation.

1.1.2 Kinetics

Kinetics is the branch of mechanics dealing with forces and torques and their effect on bodies at rest and in motion (Zatsiorsky & Zaciorskij, 2002). Sir Isaac Newton's three laws of motion describe the effects of force in terms of motion and have been the cornerstone of kinetics since they were first reported in Newton's *Principia* (I. Newton, 1687). The theoretical determination of forces responsible for human motion have been a goal of biomechanists for many years. For example, Fenn (Fenn, 1957) reported Eduard Weber's erroneous attempts in 1846 to calculate the force produced by the triceps surae when raised on the toes.

Routine measurements of the force produced by humans during locomotion was not investigated until 1872 when Carlet of France (Carlet, 1872) used pneumatic bulbs attached to the the foot to measure pressure under the heel and metatarsal regions. Carlet's system, probably because it relied on pneumatic bulbs as force transducers (Sutherland, 2005), would be unlikely to represent force as vector quantity, which would require both direction and magnitude to fully describe it. Nevertheless, Carlet's device was able to record a force-time history of normal gait similar to that produced

by a modern force platform measuring the vertical component of the ground reaction force (GRF), Figure 3.

Figure 3. Time series trace produced from Carlet's pneumatic gait device representing the vertical component of the ground reaction force of normal gait (adapted from Sunderland, 2005)

It is interesting to note, and a testament to his vision, that Carlet's device has a direct contemporary equivalent in instruments that measure plantar pressure ("F-Scan System," n.d.; "pedar," n.d.).

The first instrument reported to be capable of measuring the GRF of human gait i.e. an instrument that was able to measure and record the vector quantity not just one component of the GRF, has been attributed to Jules Amar who reported his device, the Trottoir Dynamographique, in 1916 (Amar, 1916). Amar's device was an ingenious combination of steel and cast iron levers, springs and pillars that allowed pneumatic bladders to be activated but only in directions corresponding to the three planes of motion i.e. vertical, anterior-posterior and lateral-medial, Figure 4.
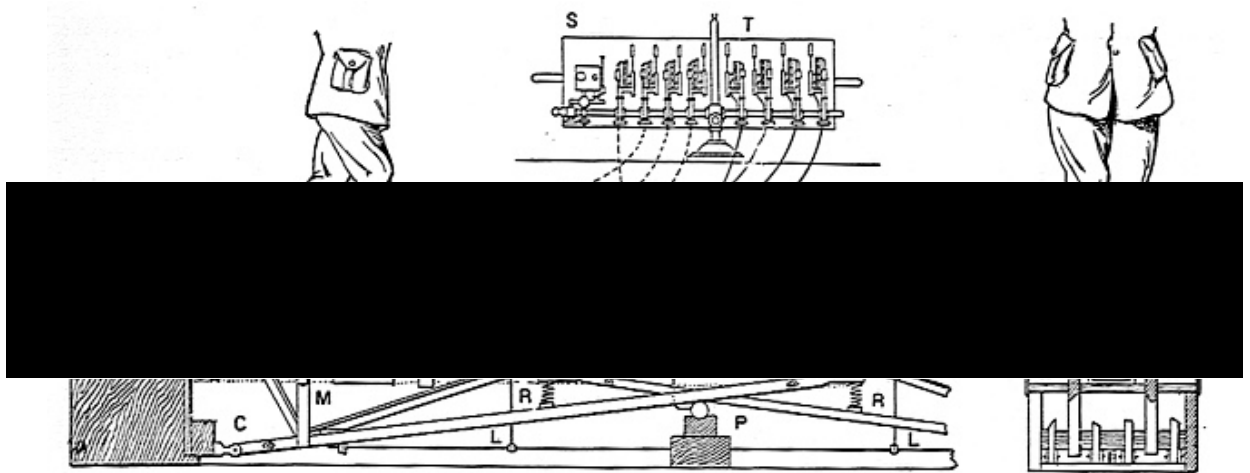
Figure 4. A schematic diagram of Amar's *Trottoir Dynamographique*.
1. Side elevation; 2. Transverse section; B. Platform for the wounded to walk; L, L.
System of levers supporting the platform via part M; R. Coil springs; C. Clevis joint; P.
Pneumatic bladder operating a diaphragm T and recorded on the cylinder S; A. Resting
landing [figure adapted and translated from (Amar, 1917)]

The bulbs associated with each plane of motion, pneumatically activated an analogue
device, the movement of which was in-turn was recorded on a "rapidly rotating
cylinder" (Amar, 1916). The machine was used to aid in the design of prosthetics
being used for amputees in the Great War (1914-1918) by attempting to mimic the gait
pattern, in terms of GRF, of able-bodied controls.

Amar's device was, in effect, a double force platform (FP) with separate
instrumentation for the left foot and the right foot, measuring 3 m long and 0.5 m wide.
The design of current FPs can be traced directly back to Jules Amar's fundamental
concepts. Although uniaxial force transducers are sometime s used in human movement
kinetic analysis, the FP remains the most widely used instrument to collect kinetic data
of human movement within a research environment. Modern force platforms can
typically sample GRF at up to 2 kHz with resolutions of ranging between 12 bits to 16
bits ("Bertec Corporation," n.d.; Kistler, n.d.; Owen, Watkins, Kilduff, Bevan, &
Bennett, 2014). Force platforms have a very large dynamic range, in terms of
magnitude of the force. At the lower end of the dynamic range, sub-newton accuracy is
possible when postural sway is being measured in children (Geuze, 2003; Rose et al.,
2002). At the higher end of the dynamic range, for example in drop jump landing
studies, the vertical component of the ground reaction force (VGRF) can exceed 4
times body weight (BW) (Bates, Ford, Myer, & Hewett, 2013; Brent & Hewett, 2006).

1.1.3 Anthropometric science

Modern principles of kinematic and kinetic measurements were established by Muybridge in 1878 and Amar in 1916 (Amar, 1916), respectively. However, it was not until 1939 when kinematics and kinetics were combined in a meaningful way. Thus enabling the systematic analyse of the forces and energy changes in the leg during walking using the process of inverse dynamics (Elftman, 1939) using a FP to collect kinetic data and cine film to measure kinematic data at a rate of 92 fps. Elftman (1939) can be considered the first person to use the methods of modern biomechanical analysis, which is dependent on a knowledge of the properties of the whole body, and body segment parameters (BSP), in terms of mass, centre of gravity (CoG) and moment of inertia. Elftman, described the process of inverse dynamics in a clear and instructive way and used a newly devised force platform capable of measuring GRF (Elftman, 1939) and anthropometric data from Otto Fischer (Fischer, 1906). Borelli appears to have been the first to have investigate the CoG of a human subject in 1679. This was achieved by having the subject lay supine on a rigid board, supported by a movable pivot, and finding the balance point, thus enabling an estimation of the CoG of the whole body (Dempster, 1955). Borelli's work (1679), while creative and ground breaking, did not provide sufficient detail (i.e. data on BSP),for use in inverse dynamics studies.

There has been interest in, and several studies undertaken on, BSP since 3000 B.C. in Egypt (Drillis, Contini, & Bluestein, 1969), however the first valid study of BSPs, in terms of usefulness to modern biomechanics, is attributed to Braune and Fischer (Braune & Fischer, 1889) and the Fischer (Fischer, 1906) who produced meticulous data derived from the study of three males cadavers. They reported the masses and positions of CoG, determined by the double suspension method, and moments of inertia for 12 body segments, namely, head, trunk without extremities, entire upper limb, arm, forearm plus hand, forearm, hand, entire lower limb, thigh, leg plus foot, leg and foot (Dempster, 1955; Drillis et al., 1969). These data were used extensively up until the 1950s (Clauser, McConville, & Young, 1969) when Dempster engaged in a continuation of Braune and Fischer's work. The need for Dempster's work was stimulated by rapid improvements in aviation and the increasing importance of space

flight in the 1950's. There was a need to provide more accurate data on the human body to the United States Airforce, because the pilot was now considered part of the aircraft, both in terms of operation and inertial properties (Dempster, 1955). Dempster's study reported extensive data of BSP, as well as other comprehensive human anthropometric data, derived from a thorough study of 8 cadavers. Figure 5, shows an example of body mass distribution reported in Dempster's study of 1955. More recently, BSP have been determined by scanning (X-ray and magnetic resonance imaging (MRI)) and other technique (Cheng, Chen, Chen, Lee, & Chen, 2000; Durkin, Dowling, & Andrews, 2002; Erdmann & Kowalczyk, 2015). However, although the current techniques offer the potential of more accurate inverse dynamics studies, in practice access to scanning facilities is a limiting factor.
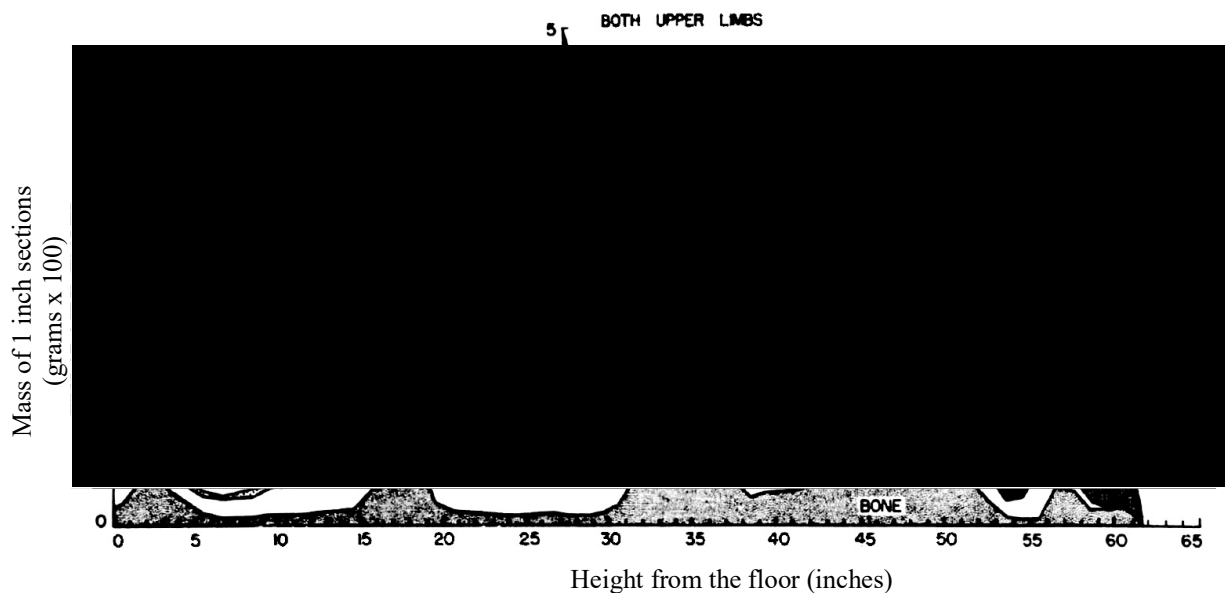
Figure 5. An example of Dempster's (1955) meticulous work, on human anthropometry and BSP, showing the distribution of body mass of a cadaver relative to its height. The weights (sic) of transverse saw-cut sections of one-inch thickness were plotted relative to height; the weights (*sic*) of bone, muscle, integument and organs in successive sections are shown also. Adapted from (Dempster, 1955)

1.1.4 The effect of loading on human tissue (bone)

The previous sections have considered some methodologies used measure, infer or derive force (and kinematic variables), this section considers the effect of force on human tissue, namely bone. Bone have several functions within the human body including support and leverage, storage of minerals and lipids, blood cell production and protection of vital organs (Martini et al., 2012; Taichman, 2005; Watkins, 2009). However, the current section will be limited to the bone's function of transmitting and resisting loads (forces and torques) both external contact forces and internal muscles forces. Bones, in terms of load bearing structural functionality, consist of cortical (or compact) and trabecular (or spongy / cancellous) bone. Both types of bone are made from the same basic building blocks, osteons (Watkins, 2009), but differ in organisation, structural appearance and function. Bones can be considered to be a hybrid material whose specific properties are matched to function (Launey et al., 2010). Bones are able to adapt their shape, composition and structure, in response to time-averaged mechanical conditions they experience.

The first documented interest in the connection between the structure of bone and functional mechanical properties is attributed to Julius Ward (Ward, 1838) and his observations of the structure of cortical and cancellous bone (Kivell, 2016). In Ward's book on human osteology he notes the similarity of the trabecular structure in the neck and shaft of a human femur to that of the mechanical structure of a street lamp bracket, Figure 6. Attention was drawn to the similarity of loading conditions for both structures. The area marked 'G' in Figure 6, is an area of low density trabecular bone and is commonly referred to as Ward's Triangle, after Julius Ward.
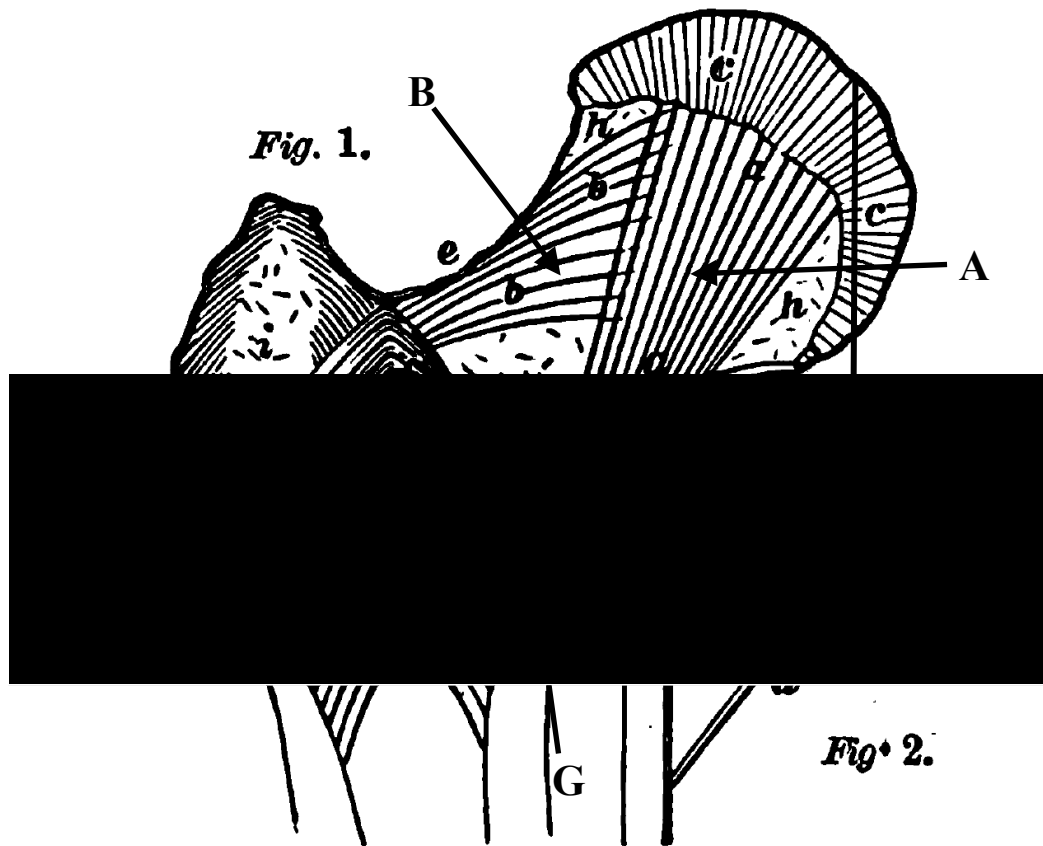
Figure 6. A schematic diagram comparing the internal structure of a human femur (*Fig. 1.*) with that of a lamp bracket (*Fig. 2.*). Ward (1938) observed that strut *a* in *Fig. 2.,* experiences compression and a bending moment about its base and that strut *b*, which is in tension, helps support *a,* the two elements providing a stable and strong structure. The analogous structures of the femur correspond to **A**, **B**. The region marked **G** (Ward's triangle)**,** corresponds to the void *g*, in *Fig. 2.*, and represents an area of low density trabecular bone in the femur. The femur supports the weight, m.g and the bracket supports the weight of the lamp, m_L.g. Adapted from (Ward, 1838)

Nearly fifty years after Ward's keen observations, Julius Wolff (1892) proposed his law of bone adaptation:

"Thus the law of bone remodelling is the law according to which alterations of the internal architecture clearly observed and following mathematical rules, as well as secondary alterations of the external form of the bone following the same mathematical rules, occur as a consequence of primary changes in the shape and stressing or in the stressing of the bones."

(J. Wolff, 1892; Julius Wolff, 2012).

Wolff's Law, in terms of functional adaptation over time due to external loading history, is still considered appropriate today, however elements of Wolff's mathematical explanation of adaptation are not correct (Ruff, Holt, & Trinkaus, 2006). Current research paints a far more complex picture combining explanations of the process of mechanostat load sensing and biological processes to model and remodel bone (Frost, 1994, 2004; Hart et al., 2017)

1.1.5 Methods of imaging bone

Not long after Wolff's Law's publication, W. C. Röntgen (1895) discovered x-rays and their application to the study of bone (Mould, 1995), Figure 7. In the 1970s x-ray computed tomography (CT) was developed, where successive 'slices' of x-ray images were reconstructed to produce a 3-dimensional (3-D) image of bone, although
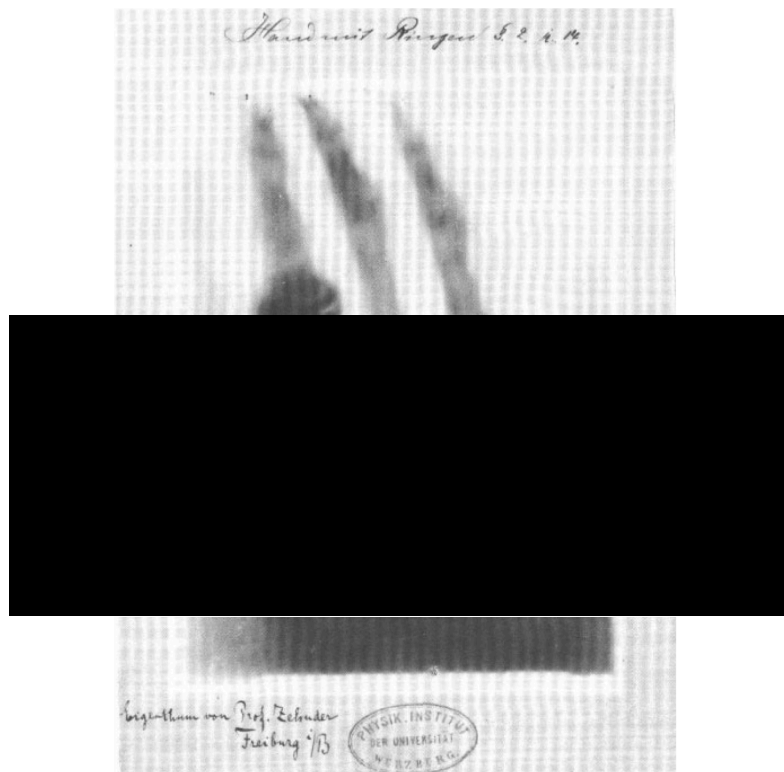
Figure 7. One of the first images produced using x-rays, Röntgen (1895). The image is of Frau Röntgen's hand. (Mould, 1995)

resolution was low (Bradley, 2008). At about the same time magnetic resonance imaging (MRI) was evolving, which used magnetic fields to produce 3-D images, not only of bone but also of soft tissue, far better than x-ray were able to and without the

need for ionising radiation (Bradley, 2008). MRI scans are predominantly used for imaging soft tissue, however with appropriate optimisation, they are being increasingly used to study bone (Singh, Bray, & Hall-Craggs, 2018). In the 1980s microCT (μCT) was developed

(Link, 2010) and in 1989 μCT was first used to investigate bone architecture, with a resolution ~ 10 μm (Feldkamp, Goldstein, Parfitt, Jesion, & Kleerekoper, 1989). More recently, laser surface scans have been used to model, with high resolution (~ 40 μm), the exterior surface of bones for both forensic osteology (Errickson, Thompson, & Rankin, 2014) and anthropological purposes (Kuzminsky & Gardiner, 2012). Figure 8., shows several examples of surface laser scans, μCT scans and MRI scans. Modern osteology and medical practice can now call on a battery of imaging techniques to study external and internal features of bone at a variety of resolutions.
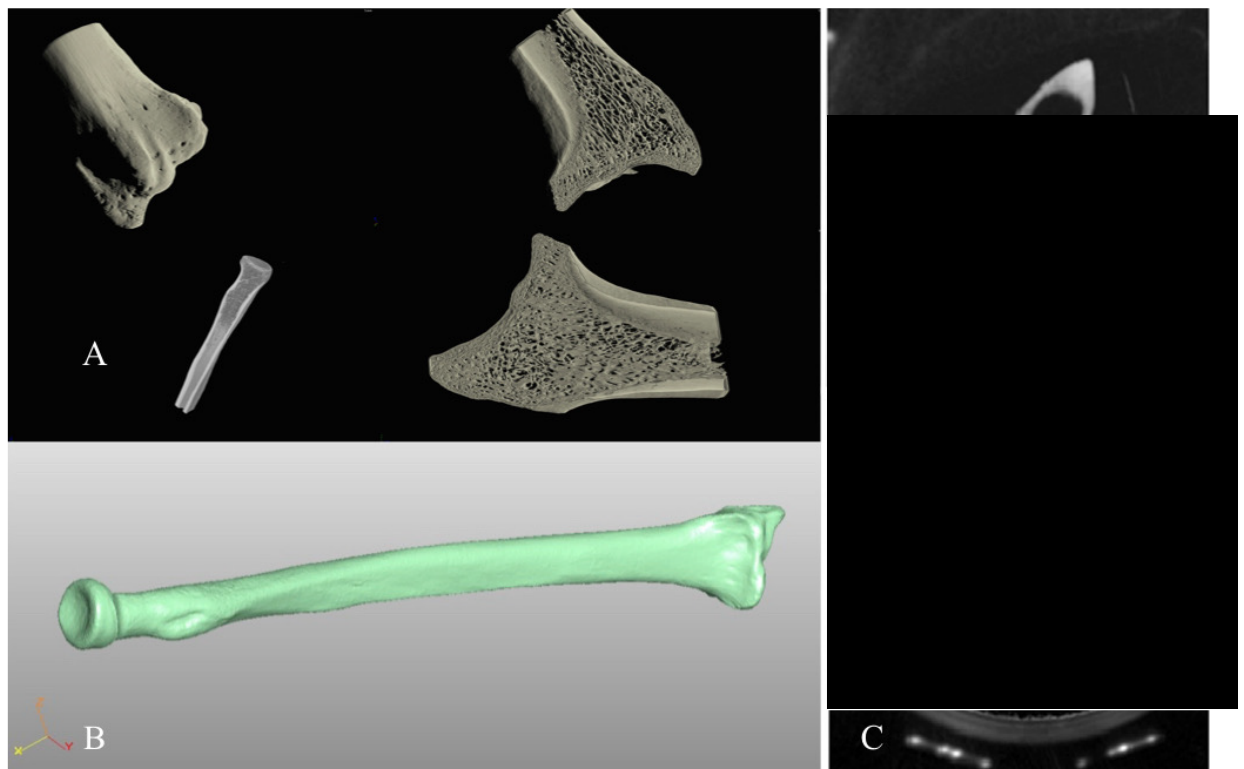
Figure 8. Examples of images produced by different scanning methods. Image A shows internal and external renders of a μCT scan of human remains (radius) from the warship Mary Rose (1545), resolution ~ 30 μm. Image B shows a laser surface scan of the same radius as in A, resolution ~ 40 μm. Images C show a transvers plane view of a tibia and fibula using MRI scanning, optimised to render bone but not soft tissue. Image C adapted from (Singh et al., 2018).

1.2 Background to the papers presented in this corpus

1.2.1 Force and the process of forward dynamics

Force is one common factor connecting the five papers in this corpus, it can be considered a complex variable, inasmuch as three base Système Internationale d'Unités (SI) units are needed to define the unit of force. Force can be defined in terms of its SI units as $Kg.m.s^{-2}$ or generally as $[M].[L].[T^{-2}]$ (where M= mass, L=length and T=time). It is a vector quantity requiring both direction and magnitude to be correctly described. It can also be defined as an influence which, if unopposed, causes a change in motion of an object (mass). The effect of force on a mass, in terms of linear kinematics was described by Sir Isaac Newton in his three laws of linear motion (I. Newton, 1687), commonly known as Newton's Laws (of linear) motion. Newton's three laws underpin classical mechanics and consequently biomechanics. They are:

1st. An object's motion will be constant unless it experiences a net force. (N1)

2nd. For a constant mass system, the rate of change of momentum is proportional to the applied force and is in the same direction as the force. (N2)

3rd. If a body exerts a force on another body, the first body will experience the same force but in the opposite direction. This force is called a reaction force. (N3)

If the forces acting on a subject (which can be considered to act on the whole body centre of gravity (WCoG) of the subject) can be measured and the subject's body weight (BW) is known, Newton's laws can be used, in a process known as forward dynamics, to determine the kinematic variables (Hatze, 2002; Kerwin, 1997; Otten, 2003). The process of forward dynamics is explained below.

A FP is a device used to measure GRF, consequently, the mass of a subject can be determined if they stand still on the FP. The motion (velocity) of the subject will then be constant (zero), therefore the weight of the subject must be equal to the VGRF, as

N1 states that if there is constant motion (i.e. zero velocity) there are no net forces acting. However, it is known that the subject has weight (due to their inertial mass and the effect of gravity), therefore the VGRF must be equal in magnitude, but opposite in its direction of action, to the weight of the subject due to N3.

If a subject performs a vertical jump off a PF and the subjects weight (and consequently mass) is known, at any point in time, the net vertical force acting on the subject can be determined by subtracting the weight of the subject from the VGRF. The acceleration can be determined using N2. The acceleration can then be used to determine the change in velocity of the subject. Similarly, if the change in velocity of the subject is known, the change in its position (of the WCoG) can be determined.

The above discussion details to the analysis of a subject at an instant. If the VGRF-time history of a vertical jump is collected and the initial conditions are arranged such that the velocity of the subject is known (zero) at the start of the jump. The corresponding velocity-time and displacement-time histories can be determined. This is the process of forward dynamics.

Instantaneous mechanical power of the WGoG (P) is determined using the relationship that instantaneous power is given by the product of instantaneous force and instantaneous velocity (C. T. M. Davies & Rennie, 1968). P can be determined using this relationship for a countermovement jump (CMJ), in which a jump is immediately preceded by a rapid dip, or a squat jump (SJ) in which a subject will squat down, rest briefly, then jump vertically upwards without any further dip or small countermovement. The ability to measure P in jumps allows strength and conditioning practitioners to assess and monitor athlete training status, as P is strongly correlated with successful performance in sports.

Whilst the above discussion details how the VGRF can be used with the mathematical process of forward dynamics to determine P in vertical jumping, it presupposes an instrument to measure VGRF to an appropriate level of accuracy and precision. A force platform (FP) is a device for measuring GRF, most commonly configured as a rigid plate with embedded force transducers symmetrically mounted, about the geometric centre of the plate, in each corner. The transducers are either of the strain

gauge or piezoelectric type. All the studies in this thesis that used a FP, used the same model piezoelectric type (model number 92866AA, Kistler Instruments Ltd., Farnborough, United Kingdom) with data logging achieved using a 16 bit data acquisition system (model number 5691A, Kistler Instruments Ltd., Farnborough, United Kingdom). When using any piezoelectric force transducer there are several important considerations; some common to all digital data acquisition systems and others of specific importance to piezoelectric systems. Any digital system needs to be able to measure force to a high enough precision to be practical for its desired use. The precision of the instrument will depend primarily on two factors. The two factors are, the threshold of the instrument in terms of measuring force and size of the quantisation step of the analogue to digital converter (ADC). The threshold of the instrument is the minimum change in force that will result in a corresponding change in the instrument output. The quantisation step, Δ, is the minimum change in the instrument's output that can be detected by the data acquisition system and is defined in Equation 1.

$$\Delta = \frac{\text{instrument output range}}{2^n} \tag{1}$$

where Δ = quantisation step, n = number of binary bits used by the ADC

A further consideration is system noise which, for a piezoelectric FP originates from two main sources. The first is mechanical noise and can be caused by any vibration in the structure of the building / room where data is being collected. The vibration will cause the FP to move i.e. accelerate, and cause a consequent, unwanted force signal in the output. The second is electromagnetic noise, which piezoelectric systems are prone to. As piezoelectric transducers produce a charge, it is necessary to condition the raw signal by processing it through a charge amplifier in order to convert the signal to a voltage. A charge amplifier has a very high input impedance (by necessity) which, if cables are not routed with due consideration, can pick-up electromagnetic interference.

1.2.2 Overview of papers

Successful performance in sports is largely determined by the interaction of environmental, anthropometric and physiological factors. The main physiological

factors are strength (peak muscle force), endurance, flexibility, speed, agility and power. Strength is usually assessed indirectly by measuring the external force that a muscle group or groups can generate in a prescribed movement such as a bench press or vertical jump. If the external ground reaction force (GRF)-time history of the movement is recorded, a number of neuromuscular performance variables can be assessed, in particular, peak force (strength, S), rate of force development (RFD) and mechanical power (P). The papers presented here describe a series of studies concerning (i) the reliability and validity of S, RFD and P in elite athletes based on GRF-time histories, measured by a FP and (ii) the utilisation of P derived in this way in the study of the development of coordination and bone health and (iii) the development of a valid and reliable measure of bone morphology.

Paper 1 (Liam P. Kilduff, Dan J. Cunningham, **Nick J. Owen**, Daniel J. West, Richard M. Bracken and Christian J. Cook, 2001) investigates the effect of postactivation potentiation (PAP) on the peak power output. PAP is a technique that may briefly increase peak power by prior activation of muscles, on start performance in elite swimmers. It assesses the effectiveness of PAP by measuring power as an outcome. The increase in P due to PAP was of the order of 5% which highlighted the need for a reliable and valid method of assessing power output.

Paper 2 (Daniel J. West, **Nick J. Owen**, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff., 2011) investigates the relationships between isometric force capacity and dynamic performance. The outcome variables from an isometric mid-thigh pull ($IMTP$) included S at different time points and RFD. Whilst S is relatively simple to determine, force at different time points is dependent on identifying the instant of initiation of the pull. This is a non-trivial problem. A new method of determining pull initiation was described that could detect an initiation even when considerable variation in GRF was present in the 'quite' period before the onset of muscular contraction.

Papers 1 and 2 highlighted the need for a reliable and valid methods of assessing of S, RFD and P. Paper 3 (**Nick J. Owen**, James Watkins, Liam P. Kilduff, Huw R. Bevan and Mark A. Bennett, 2014) describes the development of a reliable and valid criterion method of assessing peak instantaneous power output (Pp) in a

countermovement jump (*CMJ*). The paper is the first to fully investigate all variables needed to confidently define a criterion method.

Paper 4 (**Owen, N J**, Griffiths, W, & Watkins, J, 2015) describes the collection and presentation of normative values of *Pp* for children aged 7 to 11 years old. This paper is the first to describe valid, reliable normative measures of power in children.

The analysis of *Pp* in a *CMJ* has been proposed and as a marker for bone health in children (Baptista, Mil-Homens, Carita, Janz, & Sardinha, 2016a). However, as bones are not regular shaped objects, some existing methods of measuring bones' dimensions, in order to determine bone health, are not suitable e.g. cross-sectional area. Paper 5 (Mahmoodi, P, Annan, S, & **Owen, N**, 2015) describes a new method for determining a valid and reliable measure of cross-sectional area of long bones, specifically a radius bone. The measurements are derived from laser scans of bones.

1.3 Review of the Papers.

1.3.1 Paper 1. Effect of postactivation potentiation on swimming starts in international sprint swimmers

Paper 1 investigated the potential benefit of *PAP* with two outcome measures, peak forces produced at the start of a swim by means of an instrumented starting block and time to 15 m. A FP mounted at an angle of elevation of 10^0 to horizontal on the starting block, was used to collect force data for the dive and a simple kinematic video based system was used to determine 15 m times. Both these measurements were straightforward to implement and data required minimal manipulation. The time to 15 m was measured by means of a video camera, the time base (frame rate) of the video camera (50 Hz) and the camera was placed orthogonal to the direction of swimming, on the 15 m line, to provide time with a resolution of $1/50^{th}$ s i.e. 50 Hz or $1/50^{th}$ s. The FP, as it was inclined, needed a simple rotational transform applied to the force components in order to align them with vertical and horizontal (in the direction of the swim). However, the method used to determine if PAP was working i.e. if it was providing a potentiating effect, required the measurement of peak mechanical power of the whole body centre of gravity (*Pp*) from a countermovement jump (*CMJ*) taken several times, starting just prior to the *PAP* stimulus being applied.

At the time of the study, there was no published criterion method to determine *Pp* of a *CMJ* performed off a FP by means of analysis of the vertical component of the ground reaction force (*VGRF*). The specification needed to determine a valid and reliable measure *Pp* had been identified in several studies (Hatze, 1998; Kibele, 1998; Street, McMillan, Board, Rasmussen, & Heneghan, 2001; Vanrenterghem, Clercq, & Cleven, 2001). However, no single study reported all variables that needed to be controlled to obtain such a measurement. Namely, sampling frequency of the PF and integration, resolution of the FP, force range of the FP, method of determining body weight and identification of the instant the CMJ starts and consequently the start point for integration. Examples of contemporary specifications reported for the determination of *Pp* (Table 1) illustrates the lack of an agreed method and specification as well as a lack of clear reporting as exemplified by the reporting of the determination of the initiation of jump as "determined by software" (Hatze, 1998; Kibele, 1998).

Table 1. Illustrates the specification for collecting and analysing *Pp* utilising the VGRF collected from a FP. Adapted from Owen, 2008

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

Further, contemporary studies using *Pp* measured in a CMJ as an outcome measure in regression studies (Canavan & Vescovi, 2004; Harman, Rosenstein, Frykman, Rosenstein, & Kraemer, 1991; Johnson & Bahamonde, 1996; Sayers, Harackiewicz, Harman, Frykman, & Rosenstein, 1999; Shetty, 2002) reported very little information with regard to the specification and methods for determining *Pp* produced in a CMJ (Table 2).

Table 2. An example of the specifications reported in the literature for the determination of *Pp* of a *CMJ* by analysing the *VGRF*. Adapted from (Owen, 2008)

variable	Author/s (type of jump)					
	Harman et al. 1991 (SJ)	Johnson and Bahamonde 1996 (CMJ)	Sayers et al. 1999 (CMJ)	Shetty 2002 (CMJ)	Canavan and Vescovi 2003 (CMJ)	Lara et al. 2006 (CMJ)
Method of integration	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported
Sampling frequency (Hz)	500	500	500	100	500	500
Resolution of A to D converter	12 bits	Not reported	Not reported	Not reported	Not reported	Not reported
Frequency of integration	20 Hz	Not reported	Not reported	Not reported	Not reported	Not reported
Definition of time of the start of jump	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported
Jump with arms immobilised	No	No	Not reported	No	Yes	Yes
Force range	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported

CMJ = countermovement jump, SJ = squat jump

Critically, as shown in Table 2, none reported how the determination of the jump start time (t_s) was identified which is essential for reliable determination of *Pp* (Owen, 2008). Incorrect identification of t_s can cause a velocity drift, due to incorrect impulse calculations, which will increase throughout the jump. Therefore, the studies should be interpreted with caution.

In contrast to these earlier studies, Paper 1, reports a definition for t_s, although it did not report force range of the FP or resolution of the A to D converter. Although the omissions may affect the validity of the *Pp*, the reliability would not be affected. Therefore, within study comparisons remain valid. However, caution should be exercised when comparing paper 1 study values of absolute force against those of other studies. It should also be noted that *PAP* is reported to increase *Pp* by ~ 4%, consequently it is important to establish the absolute error in the determination of *Pp in a CMJ* off a FP in order to make valid conclusions about study outcomes involving the measurement of *Pp*. Future research should investigate a robust specification for the determination of *Pp* in a CMJ performed off a FP.

Paper 1 citations. Since publication (2011) this paper has been cited by 68 times. Average = 9.7 citations per year (source Google Scholar accessed 26/9/2018)

1.3.2 Paper 2. Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players

Paper 2 investigated the relationships between force/time neuromuscular variables derived from performance in an isometric mid-thigh pull (*IMTP*) and dynamic performance in jumping and sprinting. An *IMTP* consists an athlete pulling vertically upwards on a horizontal, fixed bar, at mid-thigh height, attached to a power rack (or equivalent), whilst standing on a *FP,* (Figure 9). After the command to pull is given, the athlete pulls as 'hard and as fast' as they can and the resulting force/time history is collected (Haff, Ruben, Lider, Twine, & Cormie, 2015; Stone et al., 2004). Neuromuscular variables are determined from analysis of the force/time history. Peak strength (Fp) is defined as the highest value of force produced during a period of 5 s and, as such, is straightforward to determine (Haff et al., 2005; McGuigan, Winchester, & Erickson, 2006). Other variables are dependent on the identification of a start time i.e. an instant that is the start of the athlete pulling. For example, force at 100 ms (F100) after the pull started i.e. pull initiation time (Tp), force at 250 ms (F250) after

Figure 9. Example of an isometric mid-thigh pull set-up showing the athlete standing on a force platform and pulling on a bar, fixed to a power rack.

Tp and time to Fp (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Brady, Harrison, & Comyns, 2018; Dos'Santos, Jones, Comfort, & Thomas, 2017). Figure 10, illustrates a typical force/time history of an IMTP and defines key
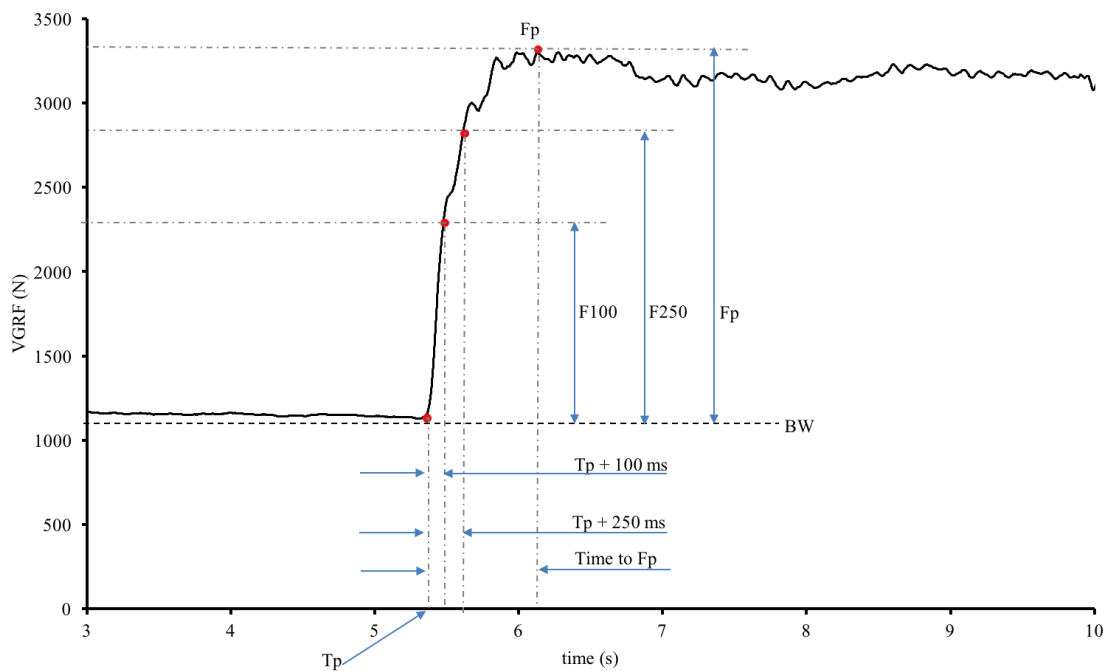
Figure 10. An example of a force/time history derived from an athlete performing an IMTP on a force platform. BW = body weight, Fp = maximum value of force during the pull (expressed as force above BW), Tp = pull initiation time, F100 = force 100 ms after Tp (above BW), F250 = force at 250 ms after Tp (above BW)

variables. However, when an IMTP is performed, due to the position the athlete assumes, there is in some athletes, a tendency to push and/or pull on the bar prior to commencement of the pull. As the athlete is standing on a FP, there is a corresponding variation of the force/time history of the period just prior to the pull being executed, in the region prior to Tp. It is difficult, without affecting the ecological validity of the test, to avoid this situation. Consequently, it is normal to collect data for an IMTP where the period prior to initiation of the pull, from which statistics used to define Tp are derived, vary considerably in terms of force stability (Figure 11A). It is therefore difficult to define thresholds, based on a mean and standard deviations of force values, in a similar manner to that described in paper 1. Papers contemporary to Paper 2, whilst reporting variables which necessitated determining Tp, did not report the
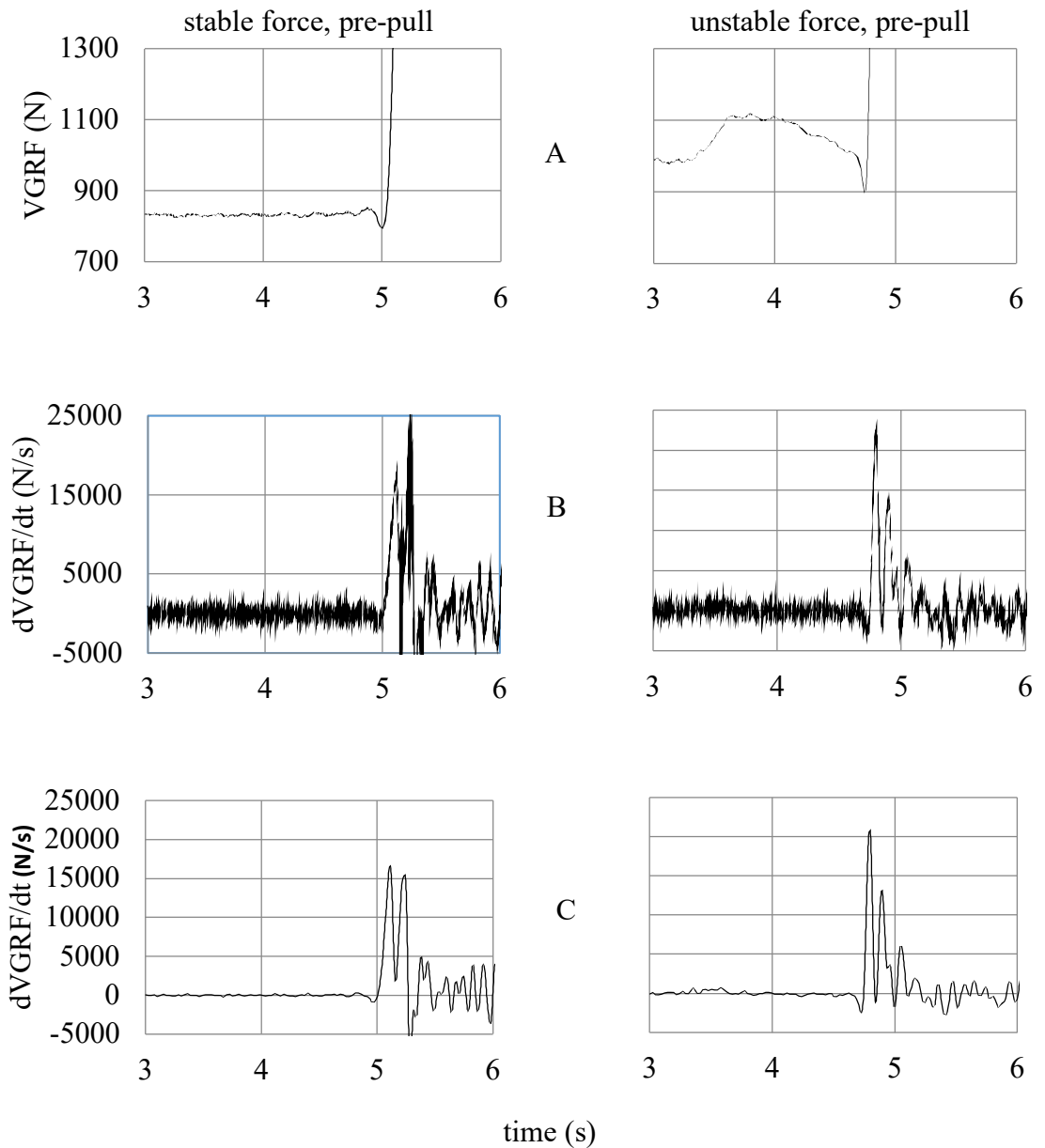
Figure 11. Two typical force/time histories of IMTP, showing the period prior to initiation of the pull and the start of the pull. 10A, illustrates examples of a stable period and an unstable period, prior to the initiation of the pull. 10B shows the corresponding 1st derivative of 10A determined from raw data. 10C shows the corresponding 1st derivative of 10A but determined from data filtered with a dual pass Butterworth low pass filter cut-off frequency 20 Hz.

methods used to determine a value for Tp (Beckham et al., 2013; Haff et al., 2015, 1997; Stone et al., 2004) or reported determination by subjective measures or arbitrary values e.g. 40 N change in force. Biases of between 20 ms to 330 ms in Tp have been

reported as a result (Dos'Santos et al., 2017). Clearly, this is unacceptable as even at the lower end of the biases, a 20 ms error in identifying Tp would cause a 20% (time) error in the determination of F100. Given that the gradient of the force/time history is at its steepest at this time, such an error would render the data unusable. Paper 2 sought to develop an objective method of determining Tp which was robust in terms discriminating between variation of pre-pull force/time history and the start of the pull.

It was reasoned that the purpose of an IMTP was to increase force (i.e. a change in force) when the pull was initiated. Also, as force is being continuously, there might also be a change in force during the period prior to Tp, it was reasonable to assume though, that the magnitude of the change of force after Tp would be considerably larger than before Tp. It followed that, using the 1st derivative of the force/time history might provide a stable metric from which to set thresholds to determine Tp. All real world signals have some degree of noise associated with them, including force/time histories derived a PF. The noise is evident in (Figure 11A) on both traces. It is well understood that the process of differentiation amplifies noise (Chartrand, 2011), consequently the 1st derivative of the raw force/time history an IMTP was unusable (Figure 11B) as the noise resulting from the process of differentiation swamped the signal. Therefore, the signal was low pass filtered using a Butterworth filter with a cut-off frequency of 20 Hz. The cut-off frequency was determined by inspection of the fast Fourier transform of the raw force/time history and also inspection of the filtered signal. It was clear that the 1st derivative of the filtered signal (Figure 11C) shows little sensitivity to the large (but slow) force changes seen in the unstable force (Figure 11A). Both 1st derivatives of the filtered data look very similar to each other, even though their parent data (Figure 11A) is very different. As such, setting thresholds based on the mean and standard deviation of the 1st derivative of the filtered raw signal, prior to the pull, was successful in identifying a consistent value for Ts. The method showed no sensitivity to large force variation, prior to the initiation of the pull, which were common with this type of test. Although this method has been applied successfully to thousands of athletes, and, as such, can be considered to be valid form an applied perspective, it is challenging to validate it to an output variable, as was the case in paper 1. Nevertheless, given the robust nature of the method reported in paper 2, it is recommended that all future research use this method for the identification of Tp. Also, future research should investigate confirming the theoretical validity of the reported method.

Paper 2 citations. Since publication (2011) this paper has been cited by 93 times.
Average = 13.2 citations per year (source Google Scholar accessed 26/9/2018)

1.3.3 Paper 3. Development of a criterion method to determine peak mechanical power output in a countermovement jump

Paper 3 can be considered a progression, in terms of methodology, from paper 1. Paper 3 reported the development of a criterion method to determine peak mechanical power (*Pp*) output, of the whole body centre of gravity (WGoG), in a countermovement jump (CMJ). Paper 1 specified some variables to measure reliable *Pp* in a CMJ, Paper 3 specifies all the variables necessary to measure to measure valid and reliable *Pp* in a CMJ performed off a FP

Movement is initiated by the conversion of potential chemical energy, stored in the muscles, into mechanical energy in the form of mechanical work. Work (W) is done when one or more body segments are moved a distance (d) by muscle forces (F) and can be represented algebraically (equation 1). In a vertical CMJ, work is done, by the muscle tendon units of the lower limbs, against gravity, on the athlete's WCoG.

$$W = F.d \tag{2}$$

The rate of doing work is referred to as mechanical power (P) (equation 2).

$$P = F.d/t = F.v \tag{3}$$
$$\text{where } v = \text{velocity}, t = \text{time}$$

The first reported use of equation 2, to measure mechanical P in vertical jumping was by Davies and Rennie (1968). They used a FP to investigate power in jumping. Their FP output an analogue voltage, that was proportional VGRF of a subject jumping, and it was recorded on an electromechanical data logging device with an effective sample frequency of 50 Hz (Davies & Rennie, 1968). Instantaneous mechanical power was then determined by first calculating the vertical acceleration of the subject's WCoG (N2) and then integrating it, with respect to time, to obtain instantaneous velocity. Instantaneous P was then calculated by determining the product of VGRF and vertical velocity (equation 2).

The method used by Davies and Rennie (1968) has become the accepted method to determine *Pp* form a VGRF/time history collected from a FP. Modern FPs collect discrete data and thus numerical methods of integration are used to determine velocity from the time-sampled force/time history (equation 3).

$$v_t = v_{t-1} + \int_{t-1}^{t} \frac{F-g}{m} dt \qquad (4)$$

where v_t = vertical velocity of the WCoG at time t, v_{t-1} = velocity one sample before time, t, F = VGRF, g = acceleration due to gravity, m = mass of the subject.

It is important to know the absolute velocity at the start of a CMJ as numerical integration of the force/time history is only able to determine the change in velocity. As CMJs start with a quiet standing phase (also called weighing period) i.e. where the athlete stands still on the FP, the velocity of the athlete's WCoG, at this point, is zero. Consequently, changes to the velocity of the WCoG can be added to zero to determine the absolute velocity.

A typical example of a force/time history of a CMJ and the corresponding velocity and power/time histories can be seen in Figure 12.
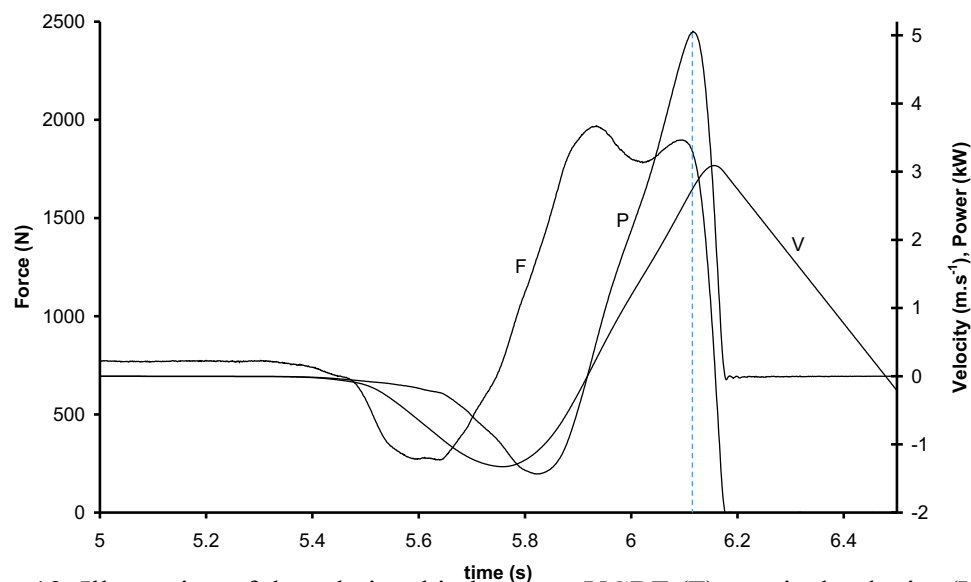
Figure 12. Illustration of the relationship between VGRF (F), vertical velocity (V) and mechanical power (P) for a subject performing a CMJ. The dotted line indicates *Pp* and its relationship with V and F.

The ability to produce high levels of *Pp* is generally considered to be a key determinant in athletic performance (Bevan et al., 2010; Cronin & Hansen, 2005; R. U. Newton &

Dugan, 2002; Sleivert & Taingahue, 2004), therefore it is important to use a valid criterion method to minimise errors and consequent uncertainty, such that maximum benefit to athletes is achieved. The above method is one such approach

Table 1, highlighted the 6 variables that need to be controlled in order to determine a valid and reliable measure of *Pp* in jumping. Paper 1 reported a reliable method to determine *Pp* in jumping by specifying t_s and reporting the sample frequency, integration frequency and BW measurement used in the method. It did not, however, justify the selection of these specification nor did it consider force range. Thus, the need for Paper 3.

Previous research reported that the vertical force range of a FP should be 3 to 3.5 times BW (Kibele, 1998). Although this is true for the net VGRF, in practice a FP determines the arithmetic sum of each of four transducers (one in each corner). An athlete performing a CMJ will transfer their weight, within their base support, from a posterior position, anteriorly towards the distal metatarsals (ball of the foot). Consequently, the front two force transducers will experience proportionately higher force values than the back. Thus, requiring the gross force range to be higher at 5.6 times BW. This is an important finding of Paper 3 as exceeding the force range on two force transducers would not be obvious from the force/time history as the sum of all four transducers is normally displayed on FP systems. This summed value would mask the forces values that exceed the range and allow potentially significant errors to go undetected. Clearly, if athlete programmes where developed using such potential flawed data, there would be a consequent uncertainty in the training prescription and potential efficacy of such training.

Another important finding of Paper 3 was the necessity to deem a jump to had been initiated (t_s) if, after the weighing period, the VGRF increased or decreased beyond threshold value. Figure 13, illustrates the need for the specification. In a sample of 15 elite rugby players, 7 players initiated a CMJ by dropping their WGoG (VGRF decreasing beyond the threshold) and 8 players initiated a CMJ by elevating their WCoG (VGRF increasing beyond the threshold).
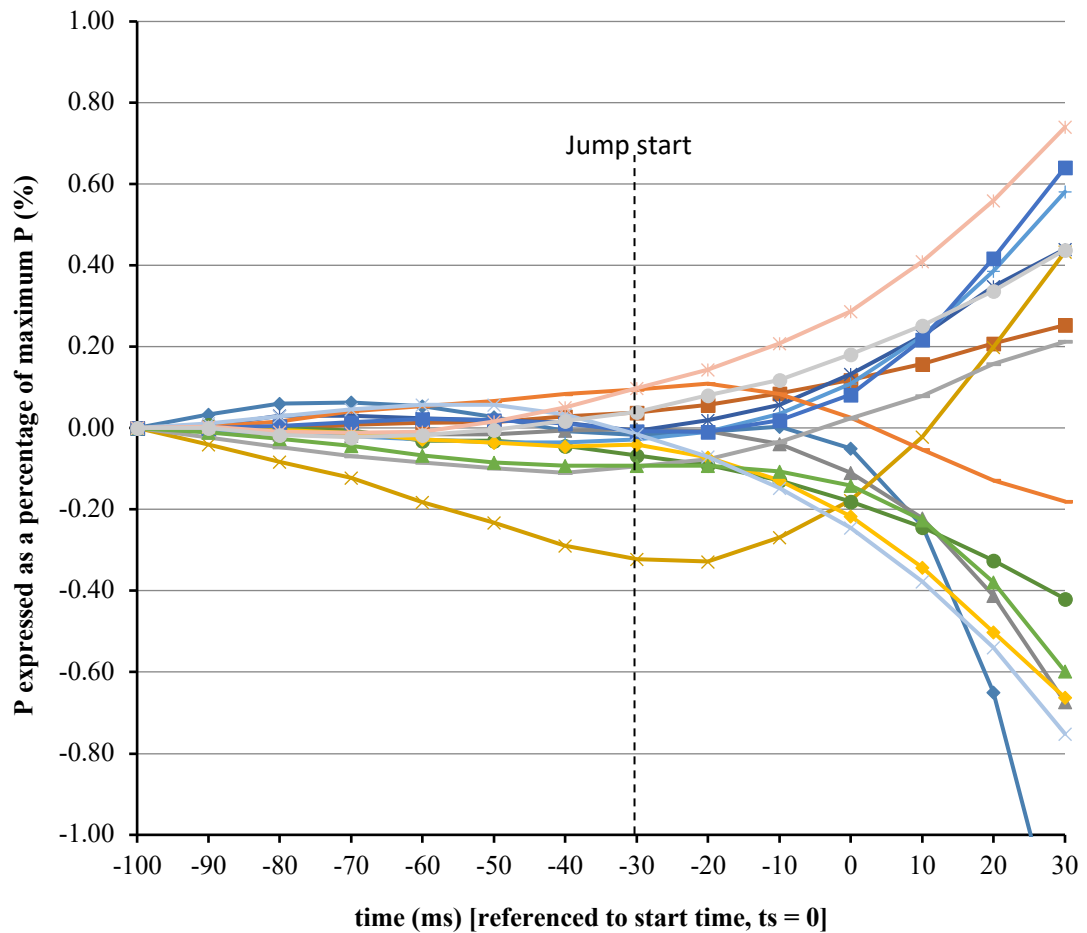
Figure 13. Power/time histories for 15 elite rugby players at the start of a CMJ. Positive power indicates an elevation of the WCoG and negative power indicates a lowering of the WCoG.

Many studies reporting *Pp* in a CMJ use methodologies that deem a jump to have been initiated only if the VGRF reduces after the weighing period, i.e. a lowering of the WCoG (Eagles, Sayers, Bousson, & Lovell, 2015; J. J. McMahon, Murphy, Rej, & Comfort, 2016; J. McMahon et al., 2017). Unpublished results from the work undertaken for Paper 3 (due to journal space restrictions) determined that methodologies using this approach to identifying the jump start (and more importantly the point from which to start the integration of the force/time history) can produce errors of around 1% in the value of *Pp*, a significant error in term of overall accuracy of the method.

Other systems measure mechanical energy in humans, for example motion capture systems using the principles of inverse dynamics. However, due to average values used for BSP and errors propagated through multiple calculations, the kinetic outputs of such systems is prone to significant error (Hatze, 2002; Rao, Amarantini, Berton, & Favier, 2006). The use of a FP and the methodology reported in Paper 3 can be currently be considered as the most valid and reliable method of determining mechanical power output of a human being.

The ability to accurately measure human power output offers unique opportunities to investigate human performance as it is a measure of a person's ability to convert potential chemical energy (stored in the muscles) into kinetic energy used for locomotion, in the form of mechanical work. Measuring Pp in a CMJ has potential applications in sports and clinical setting, many of which have yet to be explored. Paper 3 is currently the only published criterion method to measure Pp in a CMJ.

Paper 3 citations. Since publication (2014) this paper has been cited by 60 times. Average = 15 citations per year (source Google Scholar accessed 26/9/2018)

1.3.4 Paper 4. Normative data for lower limb peak mechanical power in children aged 7 to 11 years old

Paper 4, used the published criterion method for measuring Pp in a CMJ from Paper 3, to evaluate normative lower limb Pp data for children aged 7 to 11 years old (school years 3 to 6). Even though the paper was a brief communication, it represented a significant collaboration with a local education authority, in terms of gaining access to large populations of school children in a relatively short period of time. The output of this study resulted in new data being published that will form the basis of a new generation of tests for coordination deficits and bone health.

The vertical jump, as an assessment of athletic ability, was first proposed in 1921 (Sargent, 1921) and has been used extensively ever since. However, the methods of assessing the outcome measure (jump height, in the case of Sargent) have changed significantly. It is not uncommon for jump height, as measured and defined in a various different ways, to be reported as power (Patterson & Peterson, 2004) or estimates of power, derived from jump height, to be reported as power (Baptista, Mil-Homens, Carita, Janz, & Sardinha, 2016b; Janz, Letuchy, Burns, Francis, & Levy, 2015). However, such reports are misleading and incorrect. Mechanical power has an agreed scientific definition within the SI system (rate of change of energy or Watts [$kg.m^2.s^{-3}$]) and although jump height, in a vertical jump, and estimates of power derived from regression equations, clearly correlate with power they are not measures of power (Knudson, 2009; Winter et al., 2016). If valid conclusions are to be drawn from the studies measuring power it is important that the measurements are valid (mechanical power is being measured, rate of change of energy or rate of doing mechanical work) and reliable (in terms of the participants' ability to repeatedly produce the same measures to a required agreement level). However, it is common for power to be incorrectly measured and/or methodology to be lacking in detail to the extent that results might be compromised.

There are several studies in the literature reporting normative "power" values for children. For instance, a study of, n = 1845, English school children aged 10 to 15.9 years old (Taylor, Cohen, Voss, & Sandercock, 2010) reported normative values of leg power. However, the methods used did not measure power but estimated it with a

regression equation that used body mass and jump height as predictors of power. Estimates of leg power, based on regression equations, are generally recognised as being an invalid method of assessing power in an individual due to large errors (Tessier, Basset, Simoneau, & Teasdale, 2013). Further, the study used a regression equation, the Sayers' equation, developed for 18 to 21 year olds (Sayers et al., 1999) and, as such, is invalid for use with children. Given such methodological limitations, the results of the study and further studies that have replicated this methodology (e.g. Ramírez-Vélez et al., 2017) need to be interpreted with caution.

In 2006 a study entitled "Mechanography – A New Device for the Assessment of Muscle Function in Pediatrics" was published (Fricke, Weidler, Tutlewski, & Schoenau, 2006). In it the authors describe a so called "new device" for measuring kinetic variables, including lower limb *Pp*, and also report normative values for, n= 517, school boys and girls, aged 6 to 21 years old. The device they describe was in fact a FP and the methods used, which were briefly described, are those first reported by Davies and Rennie (1968). There was only one reference (Cavagna, 1975) to the very large body of work on that has accumulated since 1968 on the measurement of lower body *Pp* using a FP within the sports science literature. Surprisingly, there were no references to key papers on the subject of measurement of mechanical power in jumping by analysis of the corresponding force/time history, as measured by a FP (C. T. M. Davies & Rennie, 1968; Hatze, 1998; Kibele, 1998; Street et al., 2001).

 Expanding on the 2006 paper, Mechanography was used by Veileux and Rauch (2010) to report the reproducibility (reliability) of kinetic variables in children as well as adults (Veilleux & Rauch, 2010) and a further three studies reported normative values for lower limb Pp in children (Busche, Rawer, Rakhimi, Lang, & Martin, 2013; Gabel, Macdonald, Nettlefold, Race, & McKay, 2016; Sumnik et al., 2013). Unfortunately, none of the studies using Mechanography reported all the specifications needed to measure valid and reliable lower body *Pp* as reported in the criterion method (Owen et al., 2014). A summary of the specifications reported by these studies, in terms of lower body *Pp* measurement, can be found in Table 3. The studies had large overall sample sizes, n = 868, age range 3 to 19 years old (Busche et al., 2013), n = 769, age range 6 to 19 years old (Sumnik et al., 2013) and n = 715, age range 7 to 21 years old (Gabel et al., 2016). However the wide age ranges meant that for some ages there were small

sample sizes (e.g. only 9 males aged 5 year old and 14 females aged 19 years old). Although the Mechanography studies are well designed and have large sample sizes, the lack of methodological detail limits the extent to which researchers can be confident in the results.

Table 3. Specifications, for the measurement of lower limb *Pp* in children, reported for studies using "Mechanography" adapted from Jones (2018)

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	12000	NR	NR	NR	NR
Sumnik et al, 2013	800	NR	NR	NR	NR	NR
Gabel et al 2016	800	NR	NR	NR	NR	NR

Paper 4, appears to be the only paper to report normative values of lower body *Pp* for a paediatric population, based on a published criterion method.

The data from Paper 4, is presented in Figure 13, as a normalised probability function. It is interesting to note that, although the average *Pp* output increases with school year from 905 W in Y3 to 1367 W in Y6 and at the upper end of the distribution, 1500 W in Y3 to 2300 W in Y6, the lower end of the distribution hardly changes from 350 W for all school years. The implication is stark, if a child in Y3 is in the bottom 5th

percentile, in terms of lower limb *Pp*, they cannot be expected to improve, to any appreciable extent, in the next 4 years and possibly beyond. It is important to be able to measure *Pp* accurately in order to identify, and help, children at the lower end of the distribution.

The measurement of lower limb *Pp* in children has potential to aid in the identification and diagnosis of several diseases (Fricke et al., 2006) and conditions e.g. developmental coordination disorder. However, without an agreed method and standard of reporting neuromuscular variables, collaboration between groups, and consequent benefits, will be compromised.
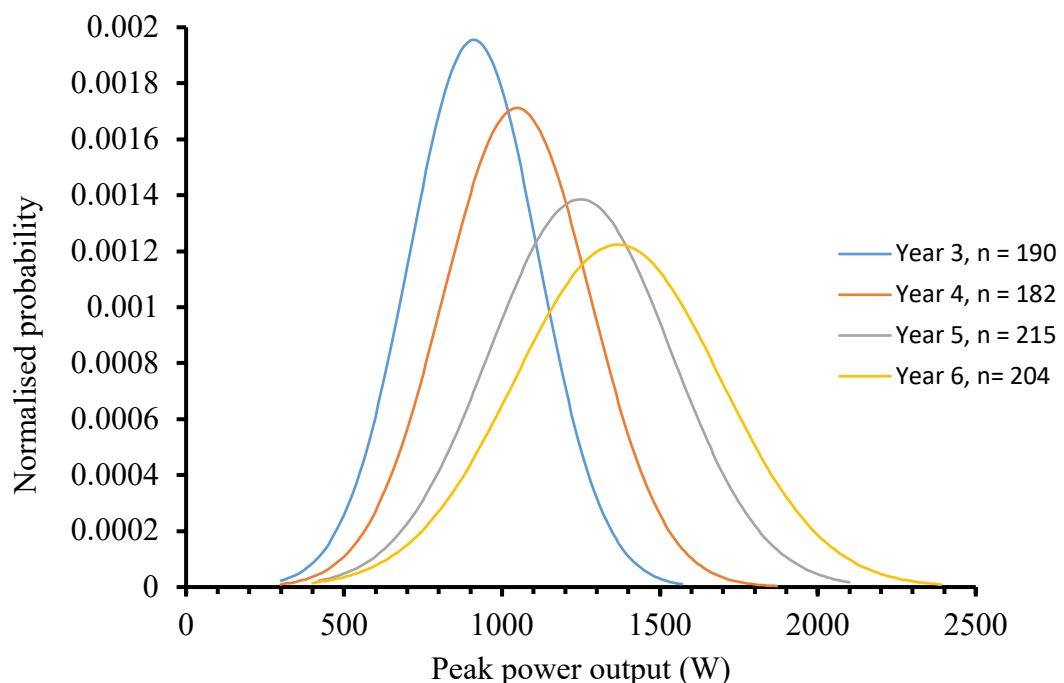
Figure 14. Distribution of *Pp* output in children in school years 3 to 6.

Given the need for an appropriate method for measuring *Pp* in children to facilitate such support, the aim of paper 4 was to identify and apply such a method. It was reasonable to assume that a specification for measuring lower limb *Pp* in elite athletes (Owen et al., 2014) would produce valid and reliable results in children or other populations, hence the results reported can be considered valid and reliable. However, it is also reasonable to assume that a specification for measuring lower limb *Pp* children would be lower than that for elite athletes. Consequently, future research

should investigate the need for population specific specifications for lower limb *Pp*. If valid and reliable results are achievable with a lower specification for a paediatric population, the cost of manufacturing of measurement equipment could decrease and hence the equipment's availability.

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1.3.5 Paper 5. A computational method of obtaining reliable measurement of periosteal cross-sectional area of human radii from laser scans

Henry VIII's warship *Mary Rose* was built in 1409 and was in service as a flagship when she sank on July 19th, 1545 whilst engaging a French invasion fleet in the Battle of the Solent (Rule, M & Charles (principe di Galles), 1982; Stirland, 2000). Five hundred men were on board when she sank (Hildred A, 2018). After sinking and due to prevailing currents in the Solent, a large section of the ship became buried under silt creating anaerobic conditions (Stirland, 1993). As a result bones were particularly well preserved, from which 97 fairly complete skeletons (FCS), 170 skull and many other bones are curated by the Mary Rose Trust (MRT) in Portsmouth (Hildred A, 2018).

It has been assumed that there were archers on board, due to the large amount of archery equipment listed on the ship's inventory (250 longbows and 9600 arrows) and also recovered from the wreck. If indeed there were archers on board, it would provide a unique opportunity to study impact of a lifetime of archery on bone development. Bones respond to loading both from external sources and from internal muscle forces by remodelling such that they are better adapted to cope with the loads they experience (Frost, 1994, 2004; Hart et al., 2017; Wolff, 1870). Work by Stirland (1993) had proposed variation in humeral heads as a marker of using a medieval longbow and a possible way of identifying the skeletal remains of archer. However, a study in 2014 determined that, due to differential loading, the radii bones were more likely to exhibit bi-lateral variation (Annan, 2014). The human remains from the *Mary Rose* present a unique opportunity to study the effects of occupational activity. Specifically, identifying archers from quantifying bilateral variation of paired radii.

In order to accurately measure the morphology of ancient bones it is necessary to use appropriate instruments, both in terms of validity and reliability while also being minimally invasive. There are several techniques that could be termed appropriate for this task, for example, µCT or peripheral qualitative computed tomography (pQCT) (Chirchir et al., 2015; Feldkamp et al., 1989; Sievänen et al., 1998), laser scanning (Davies, Shaw, & Stock, 2012; Kuzminsky & Gardiner, 2012) or MRI (Singh et al., 2018). All of these scanning technologies have strengths and weakness in terms of

specific applications, for example, surface morphology measurements. For an initial investigation into bilateral variation in paired radii, it was appropriate to start by investigate external features.   Although both μCT and MRI would be able to provide high resolution data on surface morphology, a laser scanner was chosen as the preferred instrument. The choice was made based on its relative simplicity of operation, high spatial resolution and comparatively small file sizes, which would facilitate computational speed without compromising accuracy.

Although most scanning technologies are capable of producing acceptable levels of resolution, there exists a common problem of validity and reliability, in terms of measuring the cross-sectional area (XSA) of long bones, due to their irregularities. When a cross sectional area is determined from a scan, the bone needs to be aligned to a reference surface (real or virtual), but due to the bone's morphological irregularity, this can introduce misalignments and the consequent errors (Louis, Soykens, Willnecker, Van den Winkel, & Osteaux, 1996; Sievänen et al., 1998).

Paper 5 details a computational method that overcomes these problems) by systematically measuring multiple XSAs at varying orientations and choosing the minimum value as being valid and reliable. The principle is the same as determining the true CSA of a cylinder (i.e. orthogonal to the cylinder). Consider, if an infinite number of CSAs, at varying of angles, of a cylinder were taken and the angles were not known. The true CSA could be determined by selecting the one CSA with the minimum value, which would also be a perfect circle, as opposed to an ellipse.
 Figure 14 is a graphical representation of all the XSAs, for a single bone, measured in order to produce one, final value (lowest).
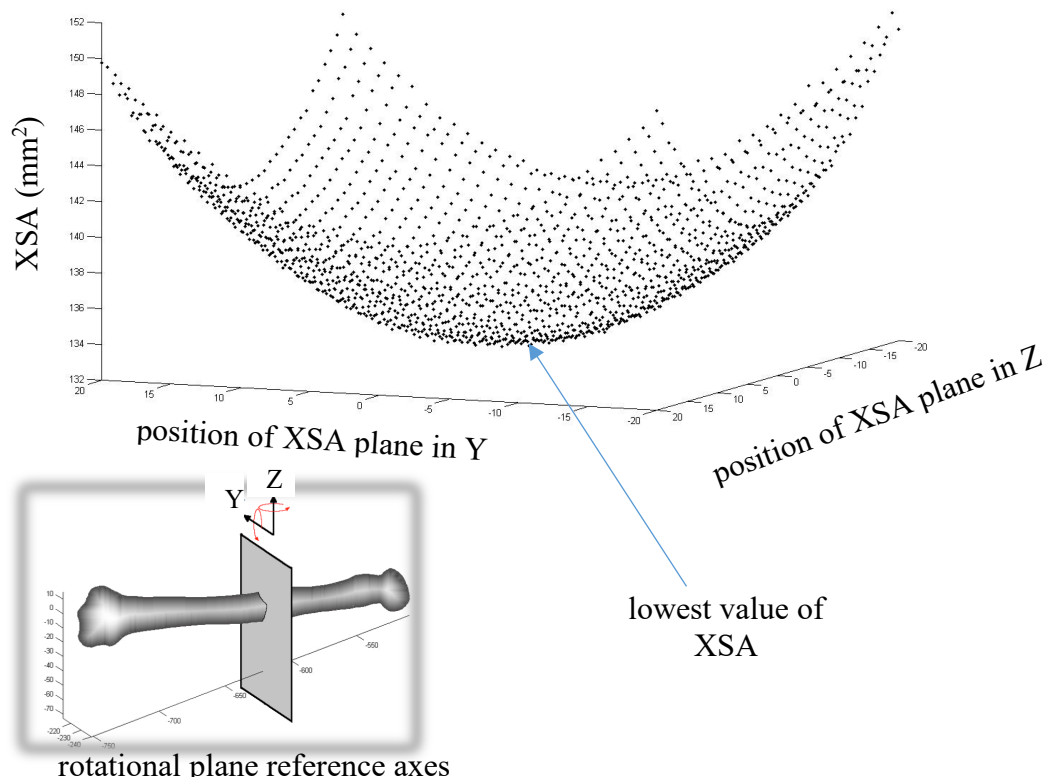
Figure 15. Cross sectional area bowl. Each dot represents one measure of XSA, the lowest value of XSA is chosen as the correct value.

The results reported in Paper 5 were a sub-set (n = 10) of the 20 pairs of radii bones (n = 40) in the MRT collection. Since publication, further analysis has been carried out on all 40 bones. The process of studying the bones was extensive. First, they were scanned and then the bony land marks were identified by rater 1, and the program for CSA measurement was run to determine the lowest value of CSA for that bone. The process was repeated for all bones. The laser scan files were then randomised and the same process was repeated by rater 1. The laser scan files were randomised again and then a second rater repeated the process. Intra and inter-rater comparisons were carried out using limits of agreement (Martin Bland & Altman, 1986). The results are presented in Figure 15.
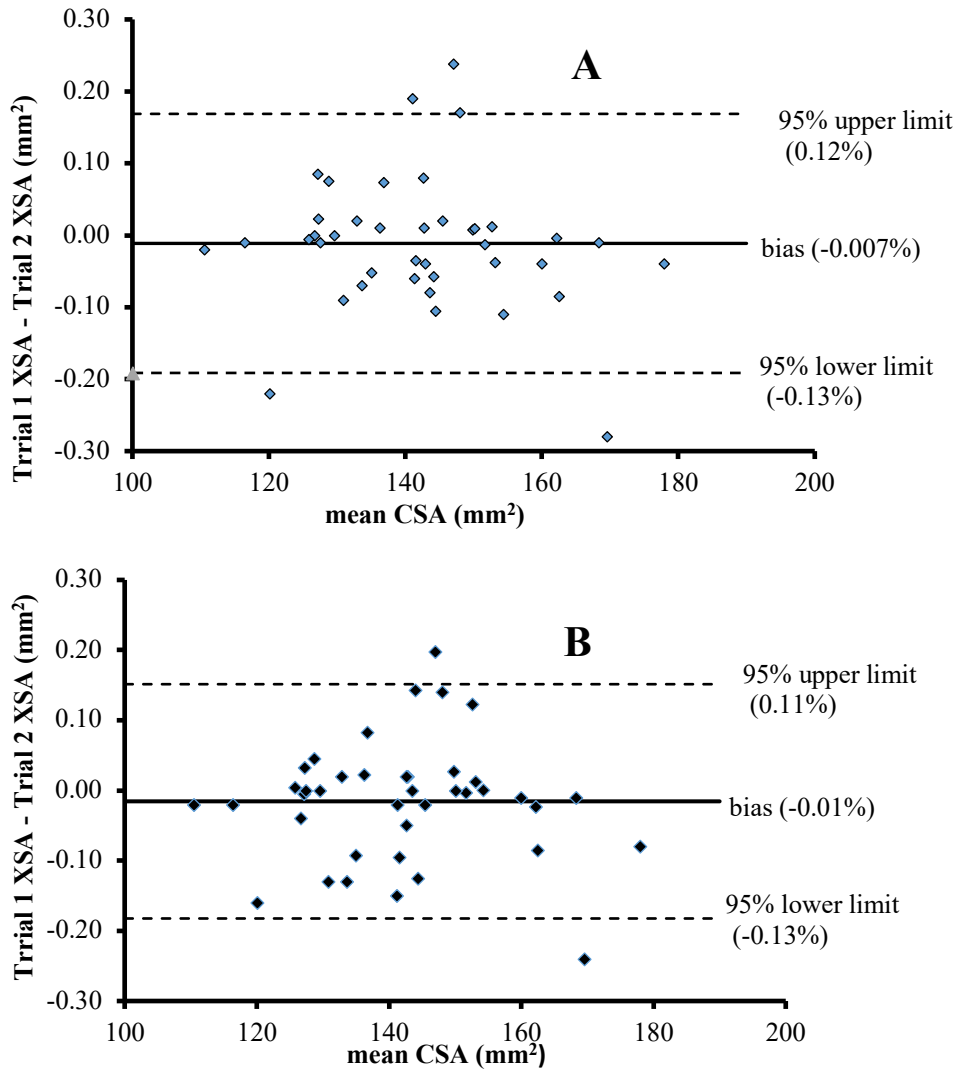
Figure 16. Limit of agreement plots for intra-rater reliability A, and inter-rater reliability B, of CSA of 40 radii.

Through an extensive process of scanning and and computational and error analysis, Paper 5 reports a valid and reliable method of measuring periosteal CSA of radii, with 95% limits of agreement (LOA) less than 0.2%. The methods used in the study can be easily adapted for use with other long bones. Bilateral differences in long bone CSA. due to occupational activity, have been reported to be an order of magnitude larger than

LOA of Paper 5's method. Bilateral CSA differences in tennis players has been reported as 14.8 % (Haapasalo et al., 2000) and 7% (Kontulainen, Sievänen, Kannus, Pasanen, & Vuori, 2003), therefore the LOA associated with Paper 5's methods could be confidently used to differentiate differences in bones due to occupational activity. The measurement of bone morphology (as well as mineral density) is becoming an important area of research, in terms of bone health in children (Baptista et al., 2016b; McKay, 2005; Riddell, Solis-Trapala, Prentice, & Ward, 2015). The methodology reported here could benefit this research by providing bone CSA measurements with much lower errors than any other reported methodology. Future research should determine optimal setting for this method of measuring CSA, in terms of the minimal number of cross sections need to produce an acceptable level of LOA. Procedures should be developed for applying this method to other human long bones and scanning technologies.

1.4 Discussion

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *science*, whatever the matter may be." (Kelvin, 1891).

Lord Kelvin's quote seems most appropriate for this collection of papers. The ability to measure a physical quantity to limits of accuracy and precision that make it practical for its applied use is fundamental to scientific endeavour. If the physical quantity, force and power in papers 1 to 4, cannot be guaranteed to be within reasonable limits it is not worth measuring them. For example, regression studies that estimate power never achieve an accuracy better than ± 15% for an individual. Although this level of accuracy might find use in determining group means, its use for measuring an individual is limited in the extreme. Paper 3 has been published for 4 years and has been cited over 60 times as a criterion method for measuring Pp in a CMJ and its rate of citation is increasing.

The use of the criterion method of measuring Pp to produce valid, reliable and accurate normative values for Pp in a paediatric population, provides the basis for many other studies. For example, it is reasonable to assume, given Pp in a CMJ measures a subject's ability to utilise energy, that it could be used as a measure of obesity. Power output decreases as a subject's weight increased above normal values (Dugan, Doyle, Humphries, Hasson, & Newton, 2004). Dyspraxia is a challenging condition to diagnose, one reason being that gross motor coordination is difficult to measure. There are over 45 tests used for assessing coordination in children, however all lack evidence of validity and reliability (Brown & Lalor, 2009). In order to produce power in a jump, intricate coordination between body segments is necessary, it is therefore feasible that measuring power jumping could be developed into a coordination test.

There is evidence emerging that Pp in a CMJ can predict poor bone health in children (Baptista et al., 2016b; Janz et al., 2015). However, the methods that currently used in

such studies to estimate power, are flawed. There exists potential for the methodology reported in Page 3 and normative values of Pp in children, reported in Paper 4, to great improve the validity of such studies. Similarly, as studies of bone health require measurements of bone morphology, Paper 5 could also have an important role in the progression of this area of study.

Paper 5 allows very accurate quantification of bone CSA, which it turn will enable osteologists to better identify which of the skeletons in the MRT's collection were those of archers. Identifying the skeletons of archers will present a unique opportunity to study the effects of a lifetime of, very specific, physical activity had on the skeleton. Such skeletons could be examined by μCT to help understand the internal structure of the bones, in a way that would be impossible for living subjects due to the large doses of ionising radiation produced by μCT scanners.

The Papers presented in this thesis provides new, valid and reliable methods and data for use in sports science, clinical science and archaeological sciences.

Appendix 1. Substantiation of applicant contribution to submitted papers.

To who so ever it may concern.

I confirm that Nicholas Owen's input to:

Normative data for lower limb peak mechanical power in children aged 7 to 11 years old

N.J. Owen, W. Griffiths & J. Watkins. Journal of Comorbidity 2015; 5: 93.

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Yours sincerely,
Wynne Griffiths B.A.

Substantiation

HB Huw Bevan ▇▇▇▇▇▇▇▇▇▇▇▇▇   👍   ↩ Reply all | ∨
Sat 29/09, 14:37
Owen N.J. ∨

To whom it may concern

I confirm that Nicholas Owen's input to:
Development of a criterion method to determine peak mechanical power output in a countermovement jump
Nick J. Owen, James Watkins, Liam P. Kilduff, Huw R. Bevan and Mark A. Bennett.
Journal of Strength and Conditioning Research. 2014. 28(6)/1552-1558 is as stated in the document
"substantiation of publications for PhD Nick Owen 20-9-18"

Regards

Huw Bevan

Watkins J.
Fri 28/09, 15:10
Owen N.J. ⌄

To whom it may concern

Date : September 28th 2018

From: James Watkins PhD
Emeritus Professor of Biomechanics
College of Engineering
Swansea University

Re: Contribution of Nicholas Owen to published research papers

I confirm that Nicholas Owen's input to:

Development of a criterion method to determine peak mechanical power output in a countermovement jump
Nick J. Owen, James Watkins, Liam P. Kilduff, Huw R. Bevan and Mark A. Bennett.
Journal of Strength and Conditioning Research. 2014. 28(6)/1552-1558

and

Normative data for lower limb peak mechanical power in children aged 7 to 11 years old
N.J. Owen, W. Griffiths & J. Watkins. Journal of Comorbidity 2015; 5: 93.

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

...

Mark Bennett
Fri 28/09, 13:23
Owen N.J. ⌄

To whom it may concern;

I confirm that Nicholas Owen's input to:
Development of a criterion method to determine peak mechanical power output in a countermovement jump
Nick J. Owen, James Watkins, Liam P. Kilduff, Huw R. Bevan and Mark A. Bennett.
Journal of Strength and Conditioning Research. 2014. 28(6)/1552-1558

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Yours sincerely,

Mark Bennett

Mahmoodi P.
Fri 28/09, 12:21
Owen N.J. ⌄

📌 ↩ Reply all | ⌄

Hi Nick,

I confirm that Nicholas Owen's input to:

A computational method of obtaining reliable measurement of periosteal cross-sectional area of human radii from laser scans
P. Mahmoodi, S. Annan and N. Owen. Proceedings of the 23rd UK Conference of the Association for Computational Mechanics in Engineering 2015, Swansea. 73-76.

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Kind Regards,
Pooya

Dr Pooya Mahmoodi (PhD)
Project Officer

██████████ ██████████
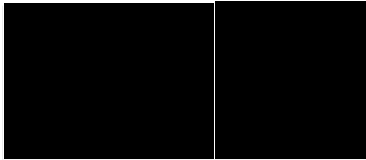
David Shearer ████████████████████████
Fri 28/09, 10:38
Owen N.J. ⌄

📌 ↩ Reply all | ⌄

To Whom It May Concern:

I confirm that the Nicholas Owen's input to:

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players
Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Kindest Regards

David Shearer

_____
Professor David Shearer
Athro mewn Seicoleg Perfformiad Elît | Professor in Elite Performance Psychology
Cyfadran Gwyddorau Bywyd ac Addysg | Faculty of Life Science and Education
Prifysgol De Cymru | University of South Wales

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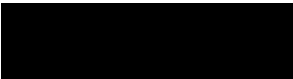
Christian Cook

Reply all

I, Christian John Cook, confirm that Nicholas Owen's input to:
Effect of postactivation potentiation on swimming starts in international sprint swimmers
Liam P. Kilduff, Dan J. Cunningham, Nick J. Owen, Daniel J. West, Richard M. Bracken and Christian J. Cook.
Journal of Strength and Conditioning Research. 2011. 25(9)/2418-2423

and

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players
Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Christian Cook
...

Substantiation

Charlie Finn

Reply all

Fri 28/09, 09:36
Owen N.J.

I confirm that the Nicholas Owen's input to:

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players
Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Charlie Finn MPhil, BSc (Hons)

(No subject)

BR

Bracken R.M.
Fri 28/09, 09:04
Owen N.J. ⌄

Good Morning Nick,

In relation to your query, I can confirm that the your input to:

Effect of postativation potentiation on swimming starts in international sprint swimmers. Liam P. Kilduff, Dan J. Cunningham, Nick J. Owen, Daniel J. West, Richard M. Bracken and Christian J. Cook. Journal of Strength and Conditioning Research. 2011. 25(9)/2418-2423

and

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players. Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff. Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

I hope this helps,

Kind regards,

Richard

Dr Richard M. Bracken
Associate Professor in Exercise Physiology and Biochemistry

Dear Nick

I confirm that the Nicholas Owen's input to:
Effect of postativation potentiation on swimming starts in international sprint swimmers
Liam P. Kilduff, Dan J. Cunningham, Nick J. Owen, Daniel J. West, Richard M. Bracken and Christian J. Cook.
Journal of Strength and Conditioning Research. 2011. 25(9)/2418-2423

and

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players
Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075

and

Development of a criterion method to determine peak mechanical power output in a countermovement jump
Nick J. Owen, James Watkins, Liam P. Kilduff, Huw R. Bevan and Mark A. Bennett.
Journal of Strength and Conditioning Research. 2014. 28(6)/1552-1558

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

BW

Liam

Liam Kilduff

Professor of Performance Science / Athro Gwyddor Perfformio

████████████████████████████████
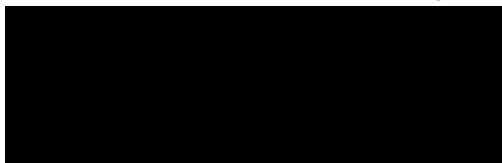
Thu 27/09, 20:40

Owen N.J. ⌄

Hi Nick,

No problem:

> I confirm that the Nicholas Owen's input to:
> **Effect of postativation potentiation on swimming starts in international sprint swimmers**
> Liam P. Kilduff, Dan J. Cunningham, Nick J. Owen, Daniel J. West, Richard M. Bracken and Christian J. Cook.
> Journal of Strength and Conditioning Research. 2011. 25(9)/2418-2423
>
> and
>
> **Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players**
> Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
> Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075
>
> is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Cheers

Dan

Sent from my iPhone
...

DW Daniel West ████████████████████

Thu 27/09, 19:02

Owen N.J. ⌄

To whom it may concern,
I confirm that the Nicholas Owen's input to:
Effect of postativation potentiation on swimming starts in international sprint swimmers
Liam P. Kilduff, Dan J. Cunningham, Nick J. Owen, Daniel J. West, Richard M. Bracken and Christian J. Cook.
Journal of Strength and Conditioning Research. 2011. 25(9)/2418-2423
and
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Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075
is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18
Regards,

Daniel

Dr Daniel West
Newcastle University Research Fellow
Institute of Cellular Medicine
Newcastle University
UK

94

Simon Annan ◂ [redacted]
Fri 28/09, 16:04
Owen N.J. ⌄

📄 Substantiation of public...
   70 KB   ⌄
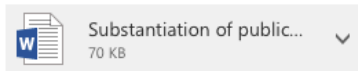
Download   Save to OneDrive - Swansea University

Dear Nick,

RE: Substantiation of Publications for PhD

I confirm that Nicholas Owen's input to the following publication:

A computational method of obtaining reliable measurement of periosteal cross-sectional area of human radii from laser scans
P. Mahmoodi, S. Annan and N. Owen. Proceedings of the 23rd UK Conference of the Association for Computational Mechanics in Engineering 2015, Swansea. 73-76.

is as stated in the document "Substantiation of publications for PHD Nick Owen 20-9-18".

Kind regards,
Simon Annan

Substantiation of publications for PhD Nick Owen

Rob NEWTON [redacted]
Today, 01:45
Owen N.J. ⌄

To whom it may concern,

I confirm that Nicholas Owen's input to:

Relationship between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players
Daniel J. West, Nick J. Owen, Marc R. Jones, Richard M. Bracken, Christian J Cook, Dan J. Cunningham, David A. Shearer, Charlotte V. Finn, Robert U. Newton and Liam P, Kilduff.
Journal of Strength and Conditioning Research. 2011. 25(11)/3070-3075

is as stated in the document "substantiation of publications for PhD Nick Owen 20-9-18"

Please do not hesitate to contact me if you require anything further.

Sincerely,

Professor Rob Newton PhD, AEP, FESSA, FNSCA, CSCS*D

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. https://doi.org/10.1152/japplphysiol.00283.2002

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