Development of a user-centred design methodology to accommodate changing hardware and software user requirements in the sports domain

A Doctoral Thesis Submitted in Partial Fulfilment of the Requirements for the Award of Doctor of Philosophy of Loughborough University

By

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Certificate of Originality

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in the acknowledgements or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

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Abstract

The research presented in this thesis focuses on the development of wireless, real time performance monitoring technology within the resistance training domain. The functionality of current performance monitoring technology and differences in monitoring ability is investigated through comparative force platform, video and accelerometer testing and analysis. Determining the complexity of resistance training exercises and whether performance variable profiles such as acceleration, velocity and power can be used to characterise lifts is also investigated. A structured user-centred design process suitable for the sporting domain is proposed and followed throughout the research to consider the collection, analysis and communication of performance data. Identifying the user requirements and developing both hardware and software to meet the requirements also forms a major part of the research. The results indicate that as the exercise complexity increases, the requirement for sophisticated technology increases. A simple tri-axial accelerometer can be used to monitor simple linear exercises at the recreational level. Gyroscope technology is required to monitor complex exercises in which rotation of the bar occurs. Force platform technology is required at the elite level to monitor the distribution of force and resultant balance throughout a lift (bilateral difference). An integrated system consisting of an Inertial Measurement Unit (both accelerometer and gyroscope technology) and a double plate force platform is required to accurately monitor performance in the resistance training domain at the elite level.

Publications

Mullane, S.L., Chakravorti, N., Conway, P.P., West, A.A., ‘Design and Implementation of a User-Centric Swimming Performance Monitoring Tool’, Journal of Sports Engineering and Technology (IMechE Part P), March 2011.

Mullane, S.L., Justham, L.M., West, A.A. and Conway, P.P., "Design of an end-user centric information interface from data-rich performance analysis tools in elite swimming", Procedia Engineering: The Engineering of Sport 8 - Engineering Emotion, 2(2), June 2010, pp 2713-2719, ISSN 1877 7058, DOI: 10.1016/j.proeng.2010.04.056.

Publications in progress as a result of PhD research

Mullane, S.L., Conway, P.P., Justham, L.M. and West, A.A., Investigating the variation in acceleration profiles according to exercise complexity using video, force platform and accelerometer technology.

Mullane, S.L., Conway, P.P., Justham, L.M. and West, A.A., Validation of a bar and waist mounted tri-axial accelerometer to monitor squat and squat jump performance.

Mullane, S.L., Conway, P.P., Justham, L.M. and West, A.A., Investigating the need to improve performance monitoring technology within a gym environment at an elite and recreational level.

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Nomenclature

1RM: One Repetition Maximum

ACSM: American College of Sports Medicine

BP: Business Process

CAD: Computer Aided Design

CIMOSA: Computer Integrated Manufacturing Open System Architecture

CNS: Central Nervous System

COG: Centre Of Gravity

COM: Centre of Mass

DFD: Data Flow Diagram

EA: Enterprise Activity

EEOEP: End of Eccentric Phase

F: Force

FFT: Fast Fourier Transform

FITT: Frequency, Intensity, Time and Type

GRAI: Graphs with Results and Activities Integrated

GRF: Ground Reaction Force

GUI: Graphical User Interface

HCI: Human-Computer Interaction

HMI: Human-Machine Interaction

HOQ: House of Quality

IDEF: Integration for DEFinition for function modelling

IMU: Inertial Measurement Unit

JH: Jump Height

LCDs: Liquid Crystal Displays

LEDs: Light Emitting Diodes

LPT: Linear Positional Transducer

P: Power

PA: Peak Acceleration

PCB: Printed Circuit Board

PF: Peak Force

PP: Peak Power

PPNSW: Peak Power No System Weight

PPSW: Peak Power with System Weight

PV: Peak Velocity

QFD: Quality Functional Deployment

RFD: Rate of Force Development

RPD: Rate of Power Development

SD: Squat Depth

SEM: Standard Error of the Mean

SSADM: Structured Systems Analysis and Designs Method

TIA: Time in the Air

TOV: Take Off Velocity

TTEOEP: Time to End of Eccentric Phase

TTPA: Time to Peak Acceleration

TTPF: Time to Peak Force

TTPPNSW: Time to Peak Power No System Weight

TTPPSW: Time to Peak Power with System Weight

TTPV: Time to Peak Velocity

TTTOV: Time to Take Off Velocity

UML: Unified Modelling Language

WIMU: Wireless Inertial Measurement Unit

Acknowledgements

To describe my PhD experience as a rollercoaster would be an understatement. At the lowest I could have walked away had it not been for the foresight and support from my supervisor Professor Andrew West who believed in the credibility of my work when I showed signs of doubt. His knowledge and advice have been invaluable over the last three and half years. I would also like to thank all the Loughborough University staff for the use of their facilities, expertise and time. To all those who I pestered for advice and guidance and those who participated in my research, I am very grateful, you each contributed to my research and made it all possible. I owe so much to my friends and family (you know who you are) who suffered along with me during the times I struggled the most. Without their unfaltering support, enthusiasm, never ending cups of tea and reminders to step away from the desk every now and then, I would never have seen the light at the end of the tunnel. Finally, a special thanks remains for the person who suffered alongside me the most. The person who never moaned when I was 'too busy', never once questioned my ability, was a constant source of motivation and somehow managed to put up with me throughout it all. You know who you are.

Chapter 1

1.0 Research overview

TARGET OBJECTIVE:

Outline the main objectives of this research and overall research structure.

TARGET RESEARCH QUESTIONS:

- *What issues must be considered when introducing new technology to the sports domain?*
- *What does this research focus on?*
- *What are the objectives of the research?*
- *How is new knowledge acquired and documented?*

1.1 Introduction

Interest in sports research and development has dramatically increased in recent years. Technology in sport is becoming a primary focus in both sports and sporting events where athletes, spectators and coaches demand accurate results. Such technology is being used to target both health and fitness benefits of physical activity. Whether health or fitness benefits are targeted, training specificity is dependent upon the user and their goals, the selection of training inputs and adaptation of the principles of training required to meet individual needs. Similarly, the technology developed to enhance performance analysis must consider the user needs and elements that support sports performance understanding.

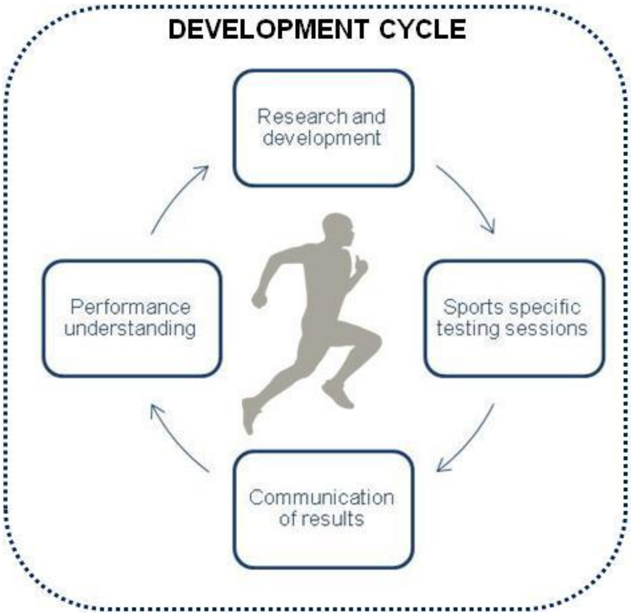


Figure 1.1 The cyclic dependency between research, testing, communication and performance understanding in the sports domain

The areas that impact sports performance understanding are illustrated in Figure 1.1. Research and development projects, specific sport testing sessions and communication of the testing results to the coaches and supporting staff is required to increase performance understanding (Reiser et al 1996). The specificity of the sports testing session and communication effectiveness both depend upon sufficient research and technology development. Sports testing sessions are reliant upon research and development to provide the technology for collecting multiple performance parameters, the value of data collection and analysis is limited if it is not communicated to the user.

Performance understanding is inhibited when the capability set of the technology and communication of data do not meet the requirements of the user (Bailey 2005). A system may be rejected if it does not perform the desired user tasks or the system functionality is too complex. A common problem experienced when introducing technology is that the user understands the current system but the developer does not, whilst the developer understands the new technology and the user does not. Therefore, understanding the user and product capability is fundamental to the design process. The gap between the developer and user knowledge can be reduced through user-centred design (Breen 1998). The knowledge required to bridge the gap between the developer and user through user-centred design is presented in Figure 1.2. Identifying and implementing methods to promote user-centred design forms a major part of this research.

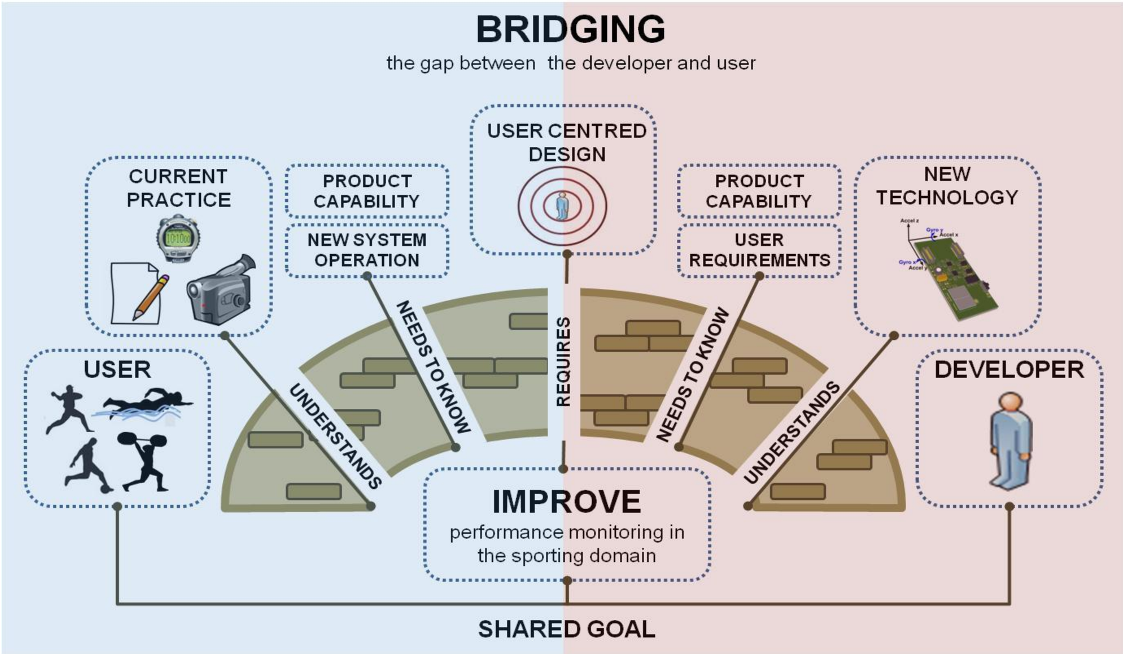


Figure 1.2 The knowledge required to bridge the gap between the developer and user to promote user-centred design

1.1 Research focus

The research conducted in this thesis aims to develop a user-centred structured design process applicable to the sports domain that considers the collection, analysis and communication of data to increase performance understanding. The main research question is as follows:

How should hardware and software design and development be implemented in the sports domain to facilitate performance understanding and accommodate changing user requirements?

To develop and apply a structured design process, a sports domain requiring technology development to improve performance understanding was selected. The resistance training domain was selected due to the lack of monitoring technology currently available in the gym environment. Current monitoring methods in the gym environment are dominated by cardiovascular machines which provide real time feedback, the inclusion of electronic user interfaces to provide feedback is becoming a necessity at the recreational and elite level (Smith 2007). Therefore, the resistance training domain requires performance monitoring technology development from a hardware and software perspective to ensure data is collected, analysed and communicated. Consequently, the focus of this thesis covers several areas to ensure that the research and development life cycle illustrated in Figure 1.1 is achieved. The design methodology needs to accommodate capturing requirements, product functionality, the hardware and software design of a system and the application of the methodology to other domains. The increase in the flexibility of the design methodology as each of the elements is targeted is illustrated in Figure 1.3. In order to target each element the research focus covers the following areas:

- *The development of a user centred design process methodology for the sporting domain.*
- *The application of the methodology to design a user-centred, elite based, performance monitoring system for the resistance training domain.*
- *Application of the methodology to software design and another sporting domain to investigate the flexibility of the methods.*

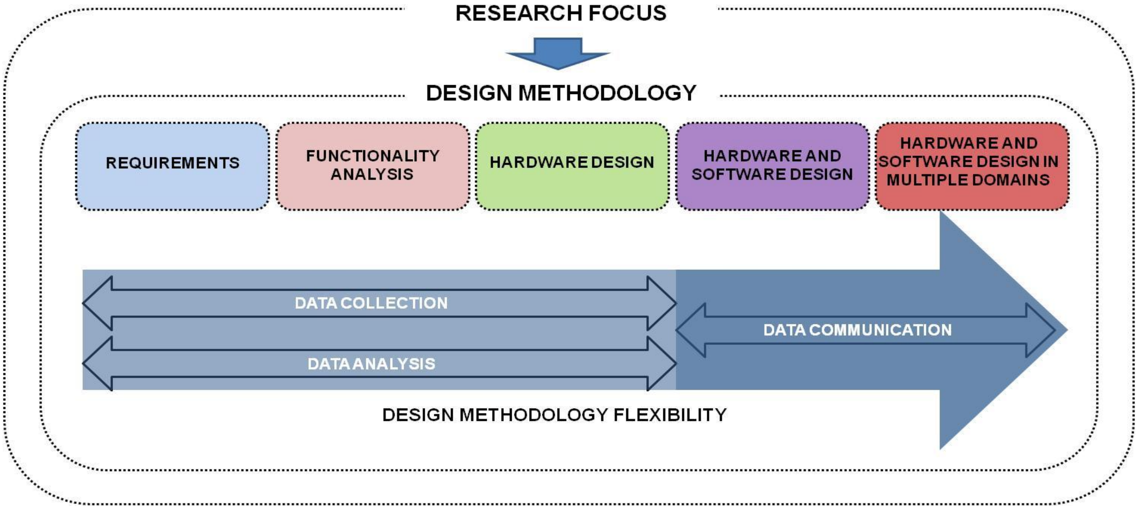


Figure 1.3 Representation of the overall research focus: To develop a user centred and flexible design methodology that accommodates the collection, analysis and communication of data across domains.

1.2 Research objectives

The research objectives have been defined to target the elements identified in Figures 1.2 and 1.3 to ensure user-centred design and flexibility is promoted. How to structure the research to promote user-centred design is discussed in Chapter 2, this methodology is followed throughout the remainder of the research. An understanding of the current practice and research in the resistance training domain to identify research gaps is achieved by conducting a thorough literature review in Chapter 3. Capturing user requirements is investigated in Chapter 4, whilst gaining an understanding of the product capability and functionality is targeted in Chapters 5-7. Embodiment design is also documented in Chapter 7 whilst consideration of data presentation and flexibility of the design methodology through software development is addressed in Chapter 8. Finally, the resultant design evaluation is discussed in Chapter 9. The objectives according to each Chapter are listed in Table 1.1.

Chapter	Objectives
2	• Design a flexible systems modelling approach that supports user-centred design to be applied to the resistance training domain.
3	• Gain an understanding of exercise physiology to understand the effects of resistance training. • Identify training inputs and outputs to determine which are most relevent to the resistance training domain. • Identify the current monitoring techniques used within the resistance training domain and investigate the benefits and limitations of each. • Identify the current gaps in research and technology development in the resistance training domain.
4	• Collect both qualitative and quantitative data to define user requirements from an elite and recreational perspective. • Re-iterate user requirements to consider user type and level of experience
5	• Conduct testing to identify the components of simple and complex exercises using video, force platform and accelerometer technology.
6	• Analyse the execution of a simple linear exercise to determine accelerometer and force platform relative and absolute validity when compared to video analysis.
7	• Determine which methods of jump height calculation are most suitable for accelerometer application. • Investigate the ability to monitor jump performance to determine readiness to perform using a waist mounted accelerometer. • Design a monitoring system that can monitor both simple and complex exercises in the gym environment.
8	• Investigate the flexibility of the design methodology by considering the commmunication of the data to the user through software design.
9	• Evaluate the research methodology and performance monitoring system design according to the original objectives and research questions.

Table 1.1 Summary of the research objectives targeted in each Chapter

1.3 Acquiring new knowledge

Acquiring new knowledge was targeted by answering the core questions identified in Figure 1.4 to develop and follow a methodology that facilitates the design of an elite system capable of monitoring a range of exercises. The corresponding Chapter(s) targeting each question are also identified in Figure 1.4. At the end of each Chapter a summary of the new knowledge is provided to demonstrate the need for each stage of research. A further breakdown of the each Chapter is presented in Figures 1.4-1.6 to illustrate the overall research structure.

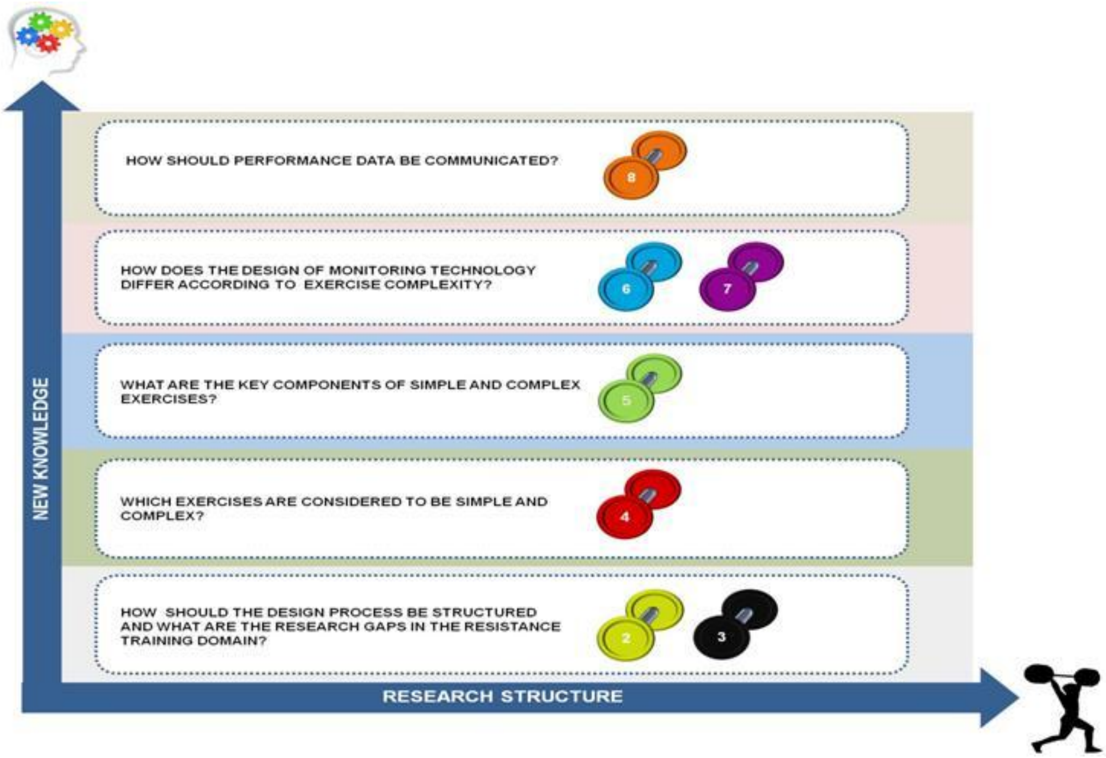


Figure 1.4 Key questions that need to be answered to acquire new knowledge and target the research objectives

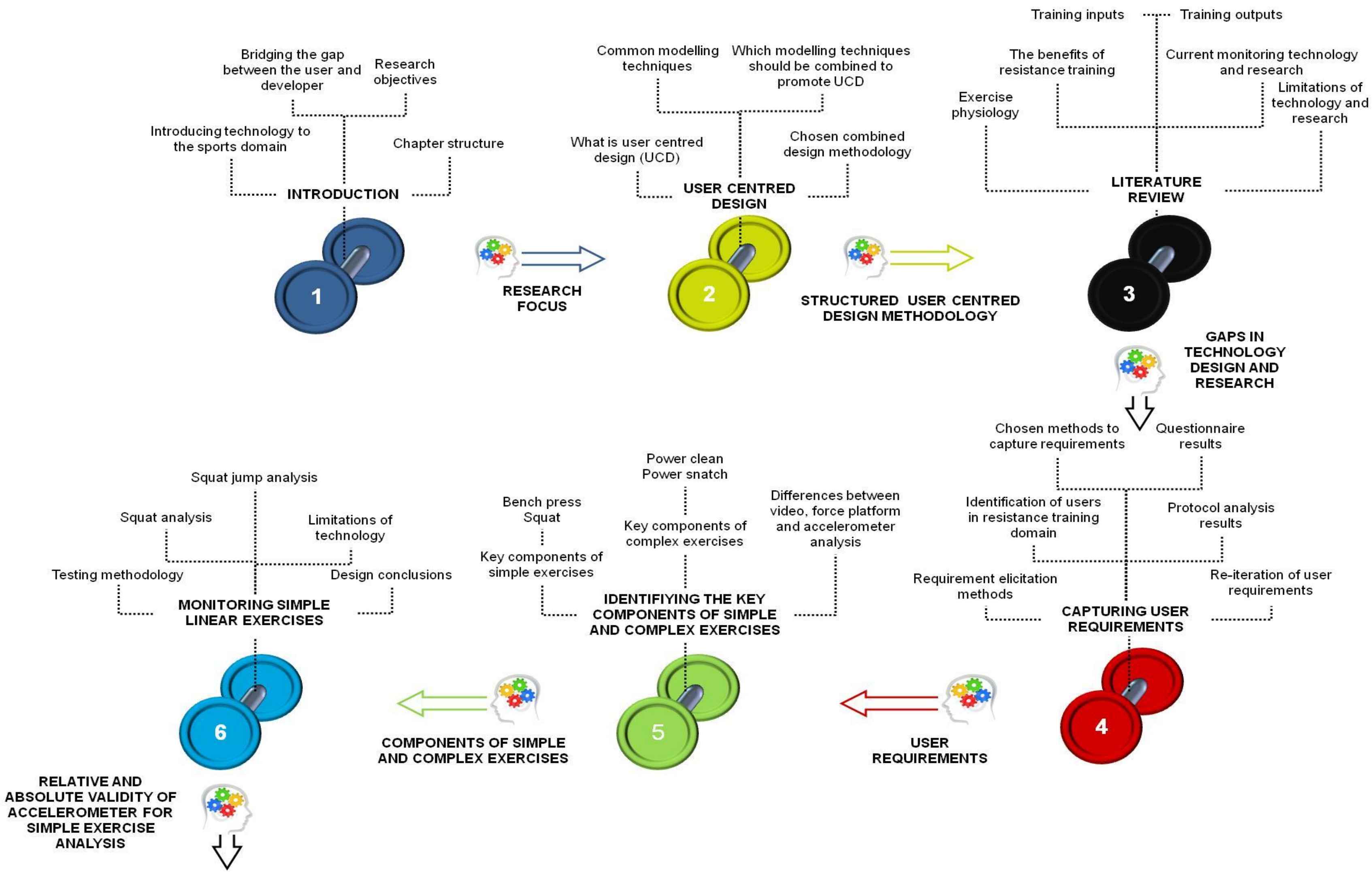


Figure 1.5 Research structure (Chapters 1-6)

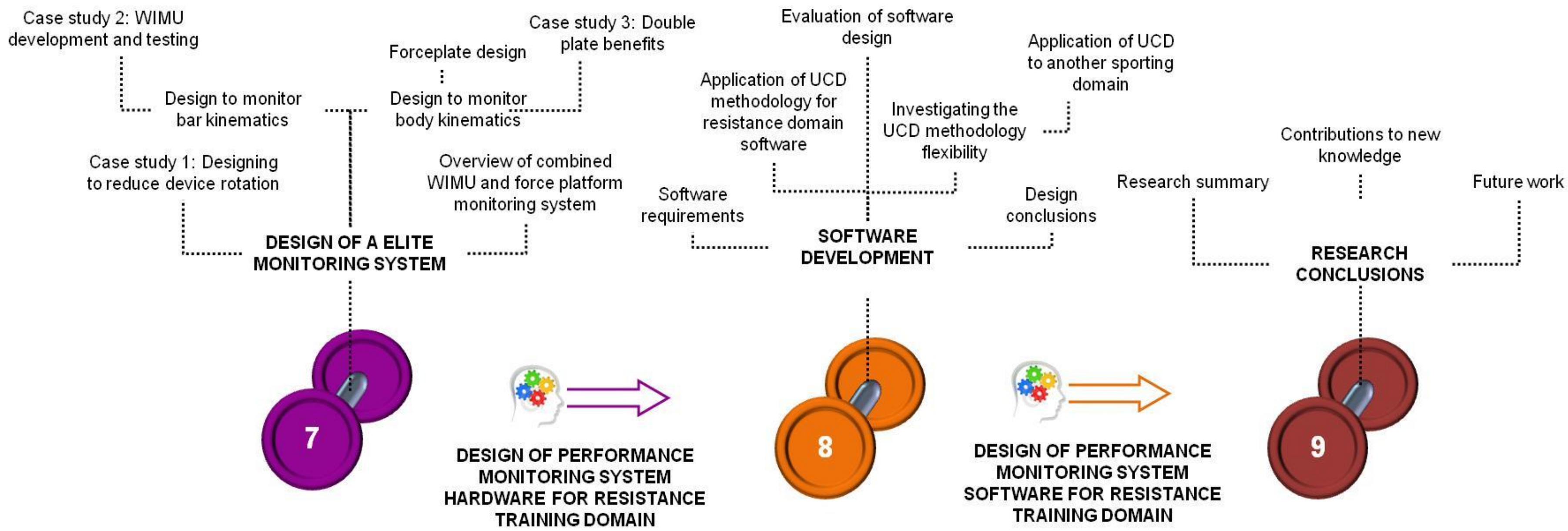
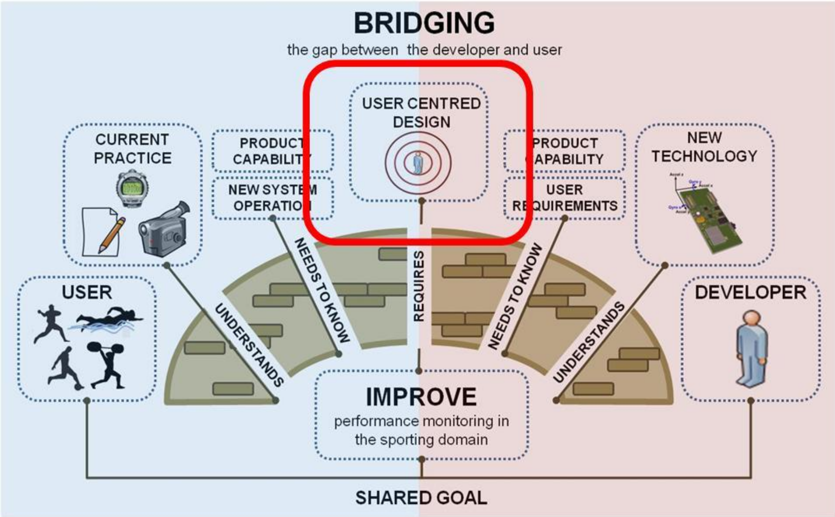


Figure 1.6 Research structure (Chapters 7-9)



Chapter 2

2.0 User-centred design

TARGET OBJECTIVE:

Design and implement a structured and combined systems modelling approach that supports user-centred design to be applied to the resistance training domain.

TARGET RESEARCH QUESTIONS:

- *Which enterprise modelling techniques promote user-centred design?*
- *Which system process models promote user-centred design?*
- *How should the modelling techniques be combined to provide a user-centred research and design methodology?*

2.1 Introduction

The aim of this Chapter is to investigate how different design process models and modelling techniques either promote or restrict user-centred design and whether different techniques can be combined to optimise user-centred design in the sporting domain. Many user modelling approaches fail due to the reliance upon one specific technique. There is evidence to suggest that substantial leverage can be gained by integrating modelling (Knudson and Morrison 1997, Luttgens and Hamilton 1997).

Relying upon one enterprise modelling technique alone does not consider a range of users and is less likely to achieve all three objectives: to collect, analyse and communicate performance monitoring data. The specificity of a system is dependent upon identification of user requirements in a particular domain and targeting these by adapting the foundation system components. As explained in Chapter 1, the aim of this research is to consider the collection, analysis and communication of performance data. Hence, how performance data is communicated to the user is crucial to performance understanding. Bridging the gap between the user and developer is reliant upon successful user-centred design (Luttgens and Hamilton 1997). The research and literature relating to user-centred design and the development of a user-centred design methodology is discussed in this Chapter.

2.2 What is user-centred design?

A visual interpretation of user-centred design is illustrated in Figure 2.1 (Noyes and Baber 1999). The need to consider all the outer domains before the interface can be developed is illustrated by the order of the rings and their distance from the user. The interface can involve both physical and logical systems. The modelling techniques suitable for both hardware and software development to increase the flexibility of the combined modelling approach are considered in this Chapter.

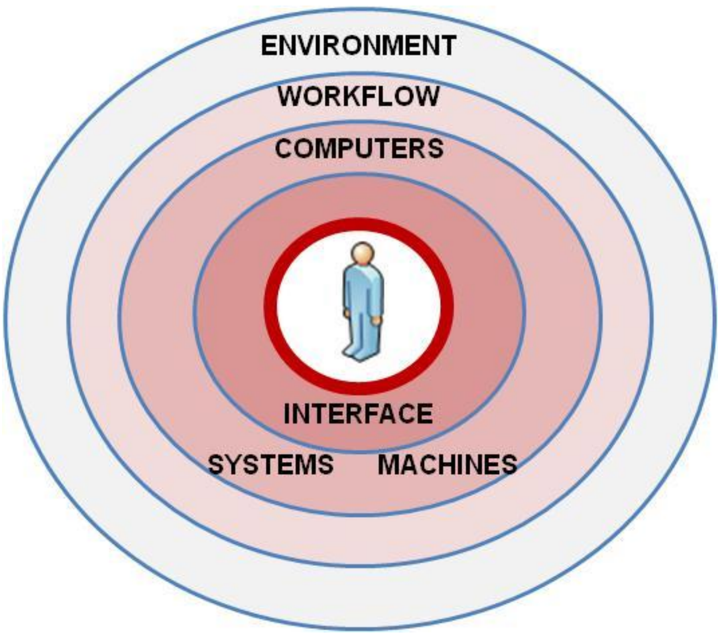


Figure 2.1 Visual representation of user-centred design (Noyes and Baber 1999)

The main purpose of user-centred design is to study human-technology interactions and ensure the system supports the user, minimises error and promotes productivity (Noyes and Baber 1999). Designing for the user, the interface and system can have a number of interpretations i.e either designing for the capabilities of the users (in terms of human physical and cognitive capabilities) or design of the work they are likely to perform (Norman and Draper 1986). The first interpretation lends itself to the traditional domain of ergonomics, whilst the second forms the term "user-centred design".

An interface does not simply refer to the point of contact between a human and computer system (even a door can be considered to have an interface), therefore the concept of a system is determined by the application (Carroll 1985). For example, the physical and operational aspects of a mechanical system are different to those of a database that stores numerous data inputs. It is suggested that in the simplest form, a system comprises many components whilst a physical or logical interface provides the link between the user and the system capability set (Noyes and Baber 1999).Whether the interface is a physical or logical application, the developer must still ensure that the user is considered at every stage of design in all design domains. It is suggested that doing so can reduce error in user-system interaction from five to one percent (Le Peuple and Scane 2003).

Standards regarding product usability and Human-Computer Interaction (HCI) are primarily concerned with; (i) the use of the product (effectiveness, efficiency and satisfaction), (ii) the user interface and interaction, (iii) the process used to develop the product and (iv) the capability of an organisation to apply user centred design (Bevan 1999). Several standards exist to accommodate the requirements for human- centred design from a hardware and software perspective. The ISO 9241-210:2010 standard provides recommendations for human-centred design principles and is intended to be used by those managing design processes for hardware and software components of interactive systems. In order to consider the collection, analysis and communication of performance data within the sports domain, both software and hardware development is required. Therefore, using this standard to identify the similarities and differences between hardware and software design requirements will facilitate the design of a user centred methodology that accommodates both perspectives.

The ISO 9241-143:2012 standard provides recommendations for the design and evaluation of ‘forms’ in which the user inputs data using dialogue boxes to update and store system information. The designer must therefore consider the options available to the user and whether they accommodate the tasks and information required to operate the system. This standard is therefore more applicable to the software system design. The main design considerations derived from the identified standard are indicated below:

2.2.1 Persona Centred Design

To promote user centred design, a ‘persona’ of the user’s need may be created. This fictional character possesses the characteristics of the user based upon observed typical behaviour, questionnaire responses and interviews. The personas created reflect the primary stakeholders of the user group. A secondary persona is often created, this persona does not reflect the requirements of the primary stakeholder group and is not the main design focus but allows the designer to considers potential human-machine interactions that may not be represented by the typical stakeholder. This allows misuse of the system to be predicted and accounted for even when the main user group is satisfied. Persona centred design is useful for creating a shared understanding of the user group and provides a context for the design.

However, personas are generalised and may be based upon characteristics that are stereotypical rather than factual. Designers should be aware that representing users with pre-determined personas could result in misconception of the actual user requirements. The focus of this research is to accommodate changing user requirements from a hardware and software perspective within the sporting domain, as the persona centred design characteristics are fixed, changing user requirements would not be accommodated should this method be used. However, observation of the user within the environment of interest provides invaluable information that may not be articulated by the user. Therefore, it is suggested that observational techniques to understand the typical stakeholders plays an important role in defining user requirements and facilitates user centred design.

2.2.2 User-centred design in the sports domain

The development of technology to monitor performance understanding in the sports domain has led to an increased reliance upon supporting technology to derive 'meaningful' results. The need to collect, store and analyse data is no longer considered exclusively for the elite and the demand for user friendly interfaces for non-expert users has increased. Despite the increased need for such user analysis and design, research in the sports domain is limited. Previous work conducted by Kranz et al 2007 outlines the challenges within the sports domain in which end users without a technical background may not be able to communicate requirements, whilst the novelty of the proposed new system may not be understood. New and adapted processes are therefore needed to elicit requirements and engineer systems (Kranz et al 2007).

2.2.3 Classification of user-centred design

User-centred design focuses on understanding the user, the user interaction with the environment and tasks rather than the presentation and behaviour for specific interaction techniques (Bowman 2004). Designing a system that requires both hardware and software functionality and user interaction must therefore target the engineering and cognitive traditions associated with Human-Computer Interaction (HCI) (Traetteberg 2002). The engineering perspective focuses on formal methods within software engineering and implementation technology, the cognitive perspective is based upon human behaviour and resultant task analysis. In order to consider hardware and software design in this research, user analysis through observational methods and task analysis and formal software modelling approaches must be investigated to identify the most user centred methods.

Numerous modelling techniques exist, whether the end product is a service, business enterprise, physical or logical system. Systems engineering process models and enterprise modelling techniques aim to capture and target user requirements (Bowman 2004). As the collection, analysis and communication of data is considered in this research, it is suggested that one technique alone is not suitable. Combining the most user-centred, flexible, iterative and systematic elements from each is investigated to target the sporting domain. An overview of this approach is illustrated in Figure 2.2, the techniques have been grouped according to systems engineering process models and enterprise modelling techniques. A brief review of systems engineering process models and enterprise modelling techniques is given to identify the elements of each that support an overall user-centred design process. The overall aim is to select an appropriate process model, identify the most suitable modelling concepts to support the model and combine the techniques that support user-centred design from an engineering perspective.

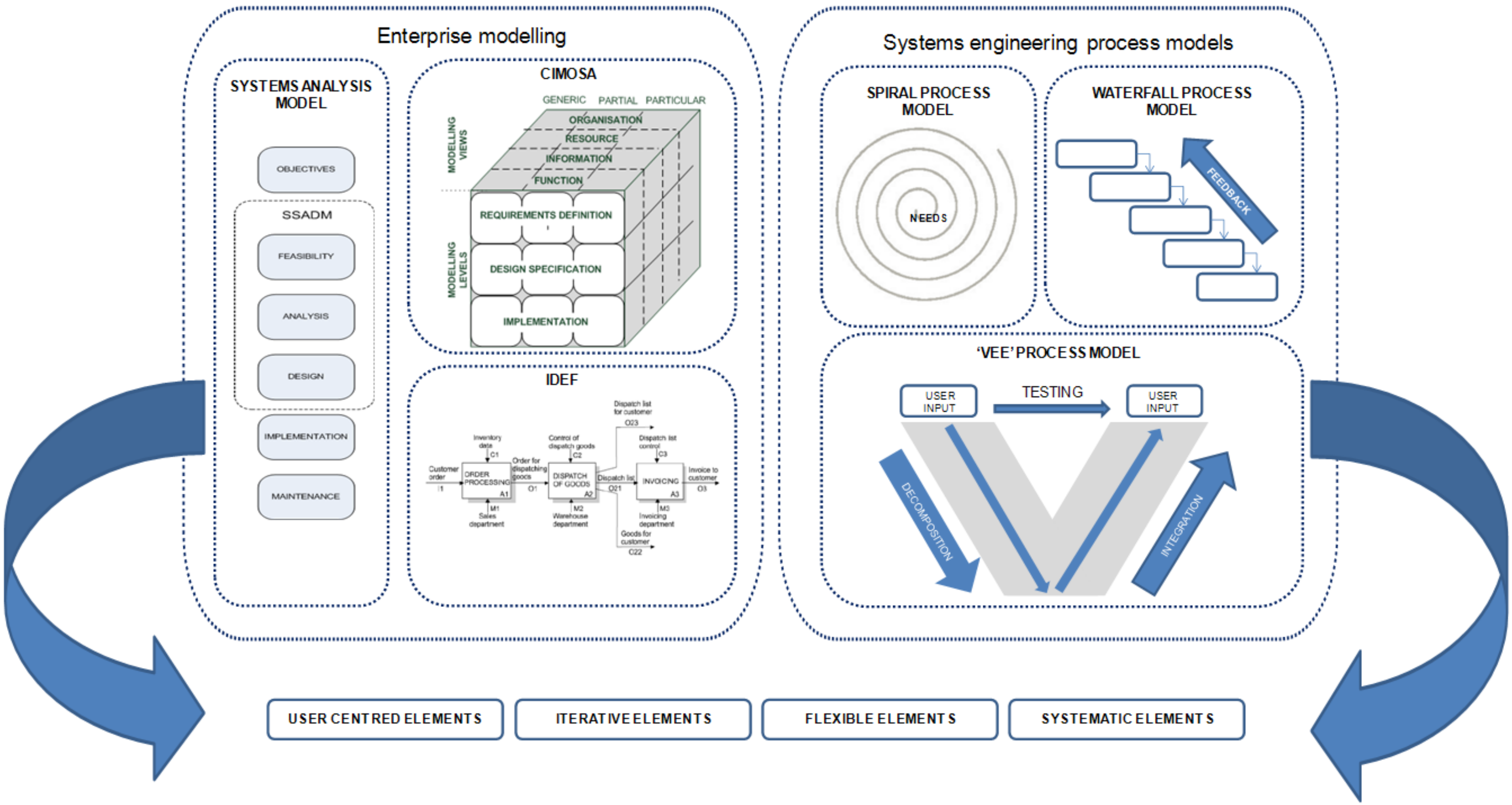


Figure 2.2 The elements to be extracted from systems engineering process models and enterprise modelling techniques to form a combined modelling approach

2.3 Systems engineering process models

There is no commonly accepted definition for systems engineering, however, the different views share some commonalities that form the fundamental objectives, these are outlined below (Landeur 1995, Galitz 2007):

1. A top down approach that views the system as a whole so that understanding how all the components fit together is considered.
2. A life cycle that considers each design stage.
3. A thorough approach to initial definition of user and system requirements
4. An interdisciplinary team approach, within which all design objectives are addressed.

How these objectives are achieved depends upon the type of design process model applied, whilst the preference for one of the process models is believed to be subjective (Galitz 2007). In order to determine the user-centred, iterative, flexible and systematic elements of each, a brief review of common process models is given in sections 2.3.1-2.3.4.

2.3.1 Waterfall process model

The waterfall method presented in Figure 2.3 was primarily designed for software development, initially only comprising of five to seven steps, the model was further developed into an eight step process. The overall technique suggests that the next step should not be executed until the preceding step has been achieved and perfected.

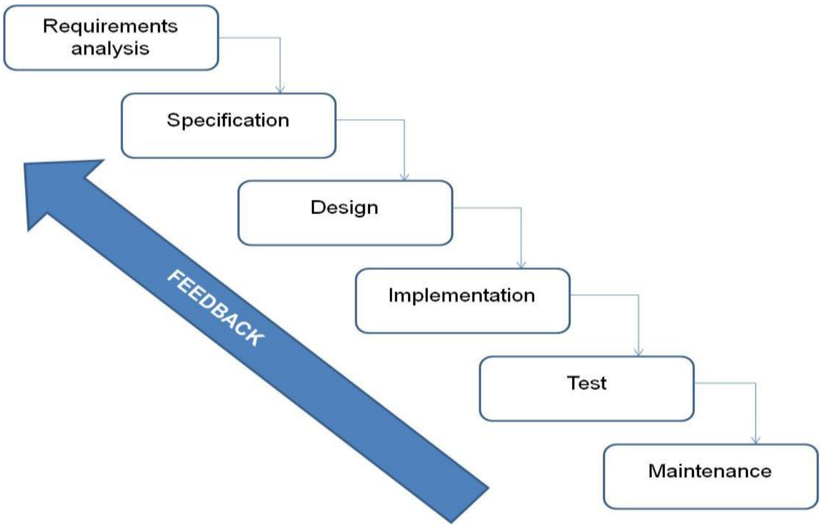


Figure 2.3 The waterfall process model adapted from Blanchard and Fabrycky (1997)

2.3.2 Spiral process model

This method is a "risk driven" approach, although it is considered to be an adaptation of the waterfall model, it incorporates the use of prototypes and re-evaluation (Blanchard and Fabrycky 1997). The model is designed to implement an iterative approach, within which the system and user requirements are revisited, prototypes produced and design requirements adjusted accordingly. This cyclical and iterative approach is presented in Figure 2.4, each turn of the spiral passes through the following stages (NASA 1994):

- Determine the objectives, alternatives, and constraints on the new iteration.
- Evaluate alternatives and identify and resolve risk issues.
- Develop and verify the product for this iteration.
- Plan the next iteration

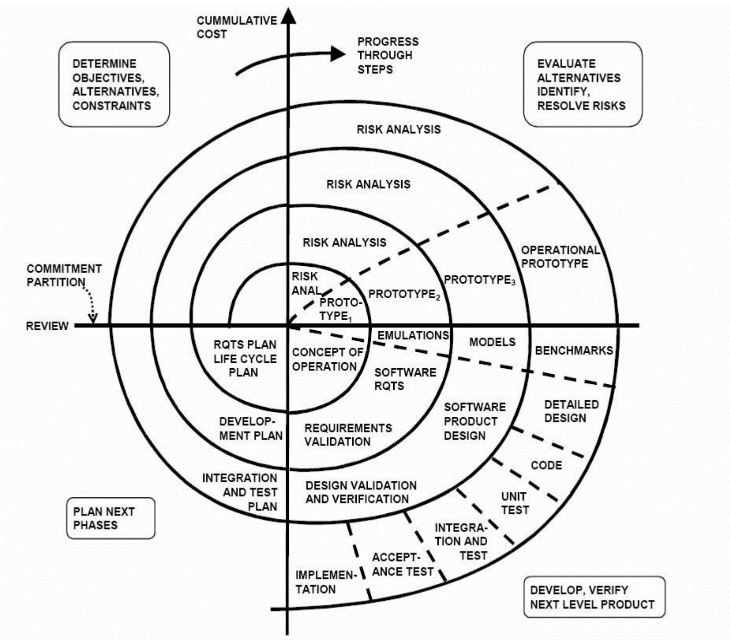


Figure 2.4 The spiral process model (Boehm 2008)

2.3.3 "Vee" process model

This method was produced to target the "technical aspect of the project cycle", the overall goal is to start with the user needs and finish with a user validated system (Nguyen 2006, Blanchard and Fabrycky 1997). It is suggested that this is achieved by decomposition of the system with an emphasis on requirements driven design and testing. All design elements must be traceable to one or more system requirement and every requirement must be addressed by at least one design element (Forsberg et al 2005). The decomposition and integration process forms the "vee" shape of the model illustrated in Figure 2.5.

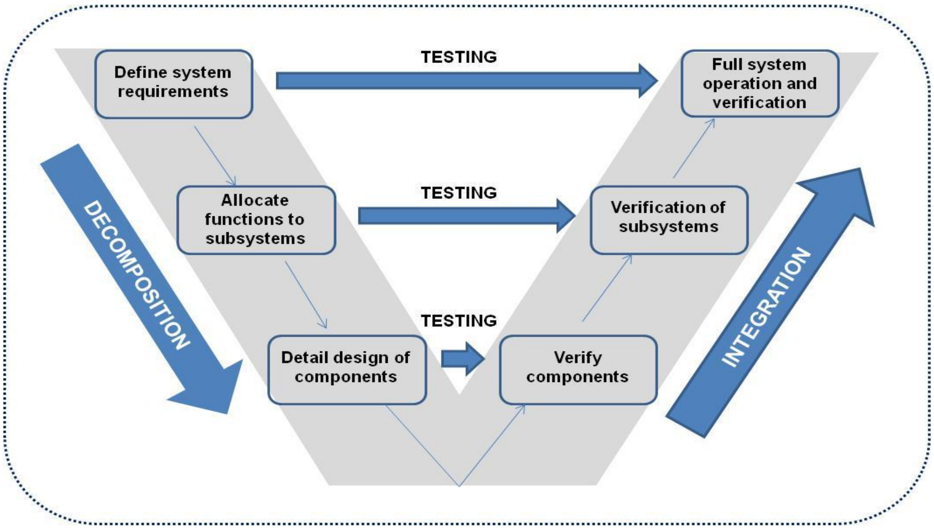


Figure 2.5 The "vee" process model

2.3.4 System engineering process model summary

Each process model has key advantages and disadvantages. However, as the aim is to promote user-centred design, the ability to accommodate changing user requirements is of most importance. The classical waterfall method, although simplistic, is not flexible or tolerant of changing user requirements, once they have been identified there is limited room for revisiting the previous step to alter the design. In contrast, the spiral model focuses on re-iteration throughout the design process allowing the requirements to be revisited. However, the developer needs to ensure that the whole system is considered in the early design stages so that problems do not occur due to unforeseen subsystems of the design. The "vee" model incorporates user input throughout the design process. It is of paramount importance that no design requirements are formed without a corresponding user requirement. Furthermore, the success of the system is evaluated through user validation. Testing is required throughout to allow for changes to the design, whilst decomposition of the overall system ensures that all subsystems are known before implementation occurs. An overview of the key process model advantages and disadvantages is presented in Table 2.1.

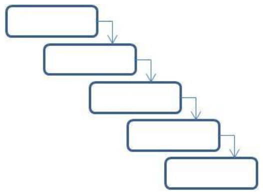
PROCESS MODEL	ADVANTAGES	DISADVANTAGES
WATERFALL 	1. Enforces the idea that time spent early on making sure requirements and design are correct saves you much time and effort later. 2. Emphasis on documentation (such as requirements documents and design documents). 3. Simple and disciplined approach.	1. Users may not know exactly what requirements they need before reviewing a working prototype. 2. Developers may not be fully aware of the capability set of the technology before testing has begun. 3. Requirements are subject to change. 4. Difficulties at the implementation stage cannot always be predicted. 5. General lack of flexibility means that it can result is both time and money being wasted.
SPIRAL 	1. Iterative approach accommodates change in requirements. 2. Flexible. 3. Some functionality of the product can be delivered quickly to the user. 4. Management of risk and uncertainty. **5.** Encourages user input in the early design stages.	1. Prototyping multiple times may be time consuming and costly. 2. Complex process, good communication required between developers. 3. Does not view system as a whole from the early stages, may cause problems in the latter stages.
VEE 	1. Verification and validation are done simultaneously. 2. Enforces a strict process flow. 3. Errors are addressed in the stage they occur. 4. The user requirements are considered at each stage. 5. Encourages user input in the early design stages and judges success through user validation.	1. Great resources needed to provide a review at each stage. 2. Complex process, good communication required between developers.

Table 2.1 The advantages and disadvantages of systems engineering process models

The “vee” process model and spiral process model would both provide a structure that would promote user-centred design, however, it is suggested that as this research is focused on the collection, storage and communication of data, the “vee” model is most suitable as it considers decomposition of the overall system. Therefore, this method would prevent overlooking subsystem elements. Despite this, the spiral process focus upon re-iteration of design and prototypes is an element that could be combined with the “vee” model to further improve the flexibility of the process model. The “vee” model and spiral model re-iteration characteristics therefore form the basis of the proposed combined modelling approach. However, how this model is followed depends upon the modelling techniques used to fulfil the process goals. A review of the most common enterprise modelling techniques is given in the nest section to determine which are most suited to a re-iterative “vee” process model.

2.4 Enterprise modelling

Enterprise modelling is an established technique which has been applied across a diverse range of business scenarios, in generic and specific applications, to aid the requirements definition, design, implementation and test of a system (Paterno and Alfieri 2001). A complete enterprise model is comprised of a set of purposeful and complementary models which describe the various aspects of an enterprise according to specific modelling constructs and semantics (Aguiar 1995). Within enterprise modelling, different paradigms and modelling constructs have been developed to represent the structure, processes, resources, information, goals and constraints of a business (Vernadat 1996, Gruninger 1996). A method of classification was proposed by Aguilar-Saven (2004) in the form of a simple selection framework presented in Figure 2.6. Four categories have been used to describe the *purposes* of business process models within a modelling framework (Fox and Gruninger 1998):

(i) Descriptive models for learning about a system,

(ii) Descriptive and analytical models for decision support, process development and design,

(iii) Enactable or analytical models for decision support during process execution and control,

(iv) Enactment models for support in information technology.

Of the four purposes, descriptions to promote learning and decision support for product development are extremely important in the early design stages. As research progresses, the need to use modelling techniques to provide decision support for product execution increases. The techniques are further divided into those that are passive and active. The ability to make changes to a system without remodelling the entire system is known as an "active approach", whilst those that require information to be reconstructed are referred to as "passive" (Smith 2007). The ability of each modelling technique to achieve the four purposes is demonstrated by the size of the oval and how far it spans across each purpose. CIMOSA, GRAI/GIM, Workflow and UML modelling provide the most flexibility as they span across at least three purposes. However, as stated by previous research, despite continual efforts, the creation of a generic modelling framework that captures information at all stages of the system/enterprise life cycle has not yet been achieved (Smith 2007). A brief review of the most commonly used techniques is presented in the following section to identify the most user-centred, flexible, iterative and systematic elements of each.

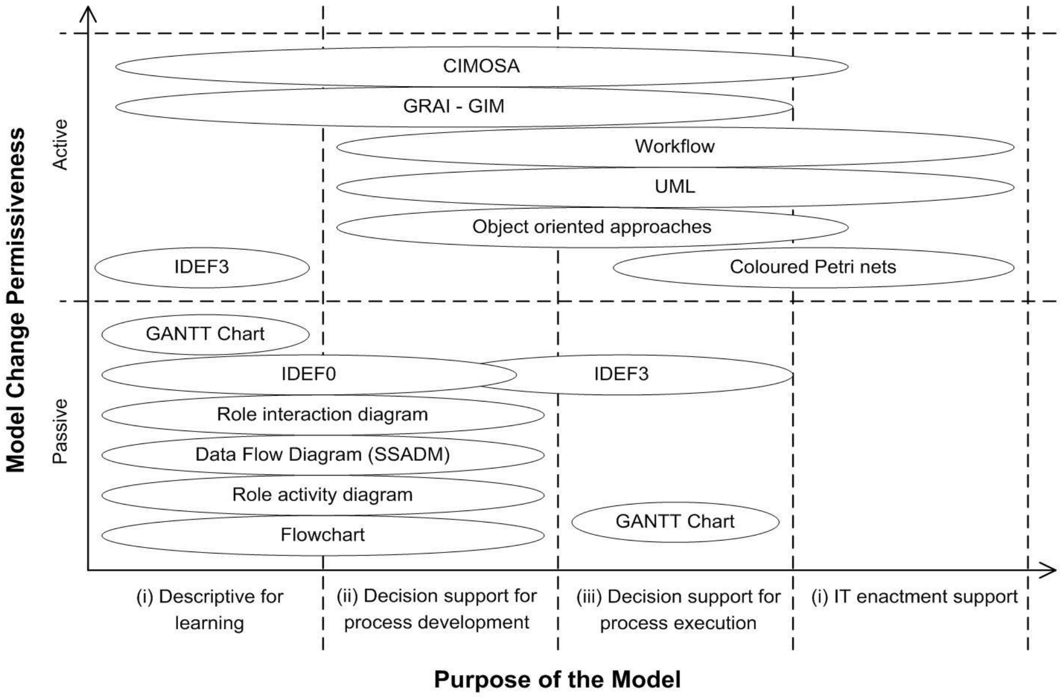


Figure 2.6 Enterprise model selection framework (Aguilar-Saven 2004)

2.4.1 IDEF

The Integration DEFinition for function modelling (IDEF) suite of modelling techniques was primarily used as a modelling and analysis method for business process engineering but is now commonly used for both systems and software engineering

(Smith 2007). The basis of the technique was formed from a structured methodology known as the Structured Analysis Design Technique (SADT) and has since expanded into multiple tools (e.g IDEF0, IDEF3, IDEF1X). The overall concept requires the modelling of decisions, actions and activities using block diagrams with supporting text to define the relationships between each (Dewitte and Porteau 1997).

2.4.2 GRAI

The Graphs with Results and Activities Interrelated (GRAI) methodology was originally designed to model automated production systems (Dougmeingts 1989). Four basic views are used to categorise the system:

1. Physical view
2. Functional view
3. Decision view
4. Information view

In contrast to the IDEF0 method which only considers the functional and physical view, GRAI incorporates decisional aspects and can therefore support changing user input (Chen 1997). However, it is also suggested that this method duplicates information that can be extracted using other techniques, the consideration of different modelling "views" is also shared by the CIMOSA technique.

2.4.3 Computer Integrated Manufacturing Open System Architecture (CIMOSA)

Computer Integrated Manufacturing Open System Architecture (CIMOSA) is an enterprise modelling framework, which aims to support the enterprise integration of machines, computers and people (Massacci et al 2007, Aguiar 1995). The framework is based on the system life cycle concept, and offers a modelling language, methodology and technology to support these goals. The reference architecture is focused on by developers to provide a "blueprint" for the subsequent design of the system should it be applied to other domains, promoting the flexibility of the framework method. CIMOSA aims to integrate enterprise operations by means of efficient information exchange within the enterprise using four perspectives (Massacci et al 2007).

1. The function view: describes the functional structure required to satisfy the objectives of an enterprise and related control structures.
2. The information view: describes the information required by each function.

3. The resource view: describes the resources and their relations to functional and control structures.
4. The organization view: describes the responsibilities assigned to individuals for functional and control structures.

Previous work details the progressive development of a system from the generic to particular level in reference to the CIMOSA reference architecture (Vernadat 1996, Gruninger and Fox 1996, Smith 2007). The reference architecture presented in Figure 2.7, provides a structure that forces the developer to work methodically from the generic to particular level, targeting all the modelling views. The formal application of CIMOSA requires dividing the system or enterprise in domains that are required to achieve a certain goal, each domain is constructed by domain processes to be communicated by events and results. Each event "triggers" a set of business processes and enterprise activities which combine to cause an end result (Vernadat 1996).

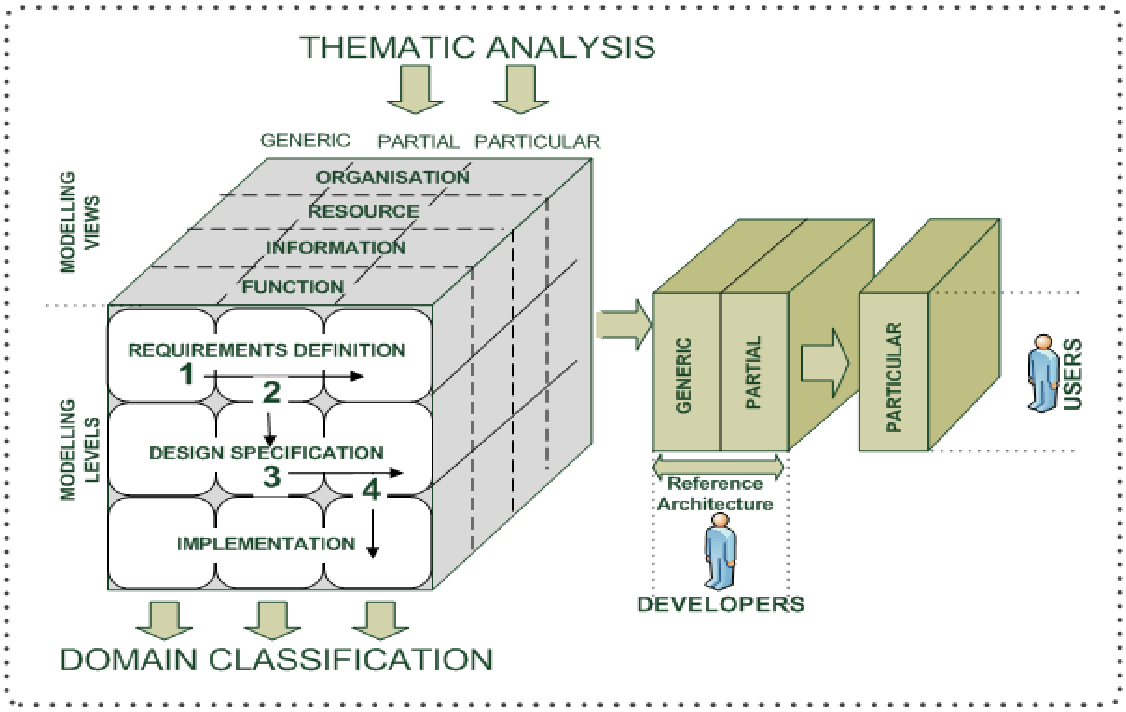


Figure 2.7 The CIMOSA reference architecture promoting design from the generic to particular level

This method allows for structured decomposition of all the processes within the system enterprise from multiple modelling views and levels. The CIMOSA framework forces the developer to progress from a generic to particular design approach by collecting detailed information through decomposition. However, although the reference architecture does provide a "blueprint", determining how to achieve this transition from generic to particular design approach is not fully defined and requires other modelling strategies such as the Structured Systems and Analysis Design Method (SSADM).

2.4.3 Structured Systems Analysis and Design Method (SSADM)

Systems analysis is considered to be a "fact-finding" stage which focuses on producing models and diagrams of the current system (Bowman 2004). It is another form of enterprise modelling that promotes descriptive learning and decision support during the process development. SSADM focuses on the feasibility, analysis and design stages of the design process (illustrated in Figure 2.8). Data flow modelling is utilised to form context diagrams and document flow diagrams which establish the internal and external entities within the domain. These models can be developed into data flow models of the proposed system, allowing the developer to predict the impact of the new system.

Using SSADM breaks down complex systems into smaller manageable blocks using "top down functional decomposition", the method requires effective use of diagrams to map the system. The scope of SSADM is clearly defined, the objective is to understand the physical aspects of the system, how tasks are currently completed and how this can be improved from a logical point of view (Bowman 2004). Utilising this modelling technique can result in an abundance of data that may be difficult to interpret. This is overcome by identification and categorisation of the separate domains within the system, a process known as domain classification. This method is shared by the CIMOSA methodology and SSADM aids this process by encouraging the developer to identify the domain processes and business processes within each domain.

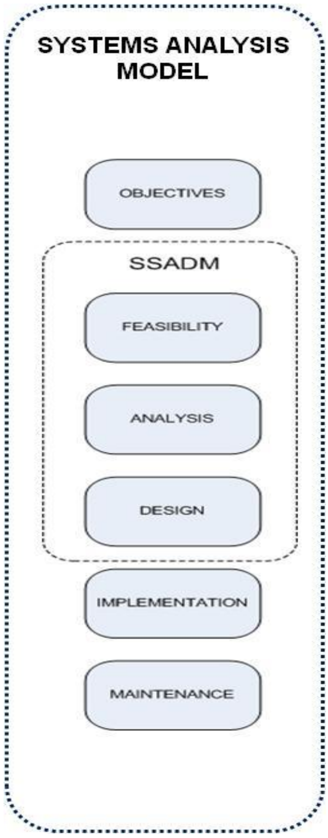


Figure 2.8 The systems development life cycle using SSADM [Bowman 2004)

2.4.4 Domain Classification

Domain analysis supports system reuse by capturing domain expertise and can also support communication, training, tool development and system specification and design (Kang 1990). It is achieved by examining the functions that need to exist separately within a system and the relationship between each. The structured process enables the developer to target the requirements defined previously at the partial level in the CIMOSA cube whilst incorporating the entity relationships needed to improve the communication links at the particular level. Research has suggested that domain classification should occur before systems analysis is conducted (Prieto-Diaz 1987), however, it could be argued that appreciation of the communication channels within the system cannot be understood until the data flow types and directions have been identified (Mullane 2010).

2.4.5 Business process analysis

Investigating the tasks likely to be executed within the classified domains requires further analysis at a lower level. Using the domain process breakdown as a starting point, business process analysis can be employed to further analyse the processes that will be conducted in each domain and the functionality needed to support this. The decomposition of the domain process via the business processes leads to identifying the enterprise activities. Business processes organise and link enterprise activities based on their sequence of execution, reflecting the behaviour of the enterprise (Ortiz 1999). Modelling the domain process within the categorised domains further decomposes the generic structure into specific "use-case" scenarios ensuring the developer progresses to the particular level of the CIMOSA reference architecture.

A business process is a set of logically related business activities that combine to deliver something of value to the customer (Cousins and Stewart 1992). The method involves decomposing the processes within the environment and identifying the internal or external entities required to carry out such processes. Using functional decomposition, operational aspects of the new system are gained from the user perspective. This allows the developer to design a software structure that accommodates the order of execution and the outputs desired by the user. Business process analysis was conducted in the weightlifting domain to decompose functionally the processes required to operate the proposed system (Kosanke 1995).

2.4.6 Evaluation of current enterprise modelling techniques

Although the framework proposed by Aguilar-Saven (2004) provides a guide for selection, it is suggested that considering only the four purposes and two approaches (passive and active) does not fully communicate the functionality of each method. The framework does not demonstrate the reliance of the more applicable techniques upon the less flexible methods. For example, as previously discussed, the CIMOSA framework would not be effective if decomposition at a lower level was not conducted, i.e without the inclusion of SSADM and data flow modelling techniques, domain processes, business processes and enterprise activities would not be identified, preventing the transition from the generic to particular design level. Consequently, SSADM is a construct of the CIMOSA framework, supporting further the view that enterprise modelling techniques are less effective if used in isolation and are likely to be more "user-centred" should a combined approach be taken (Peuple and Scane 2003). As a result, it can be concluded that the most effective design approach would utilise the CIMOSA reference architecture and incorporate the SSADM approach to enable decomposition of the system.

2.4.7 Combining process models and enterprise modelling techniques

Using the enterprise modelling techniques in isolation is not effective (Noyes 1999) since a process model to which the modelling techniques can be applied needs to be identified. As a result, it is suggested that elements of the "vee" process model are combined with the CIMOSA reference architecture and SSADM modelling techniques. The overall combination of methods is presented in Figure 2.9. The importance of testing at each stage, decomposition and integration of subsystems, incorporating user input in the initial stages and evaluating the system through user validation are all concepts that are extracted from the "vee" process model. Working from a broad design perspective and encouraging the developer to collect user and system information to narrow the design, is supported using the CIMOSA reference architecture which progresses from a generic to particular design level. The decomposition process is achieved using SSADM techniques, through identification of domain processes, business processes and data flow modelling. The ability to accommodate changing user requirements is highly dependent on the iterative nature of the design process. As discussed previously this is a key element of the spiral process model. The importance of iterative design and how it can be applied to the combined methodology is discussed in the following section.

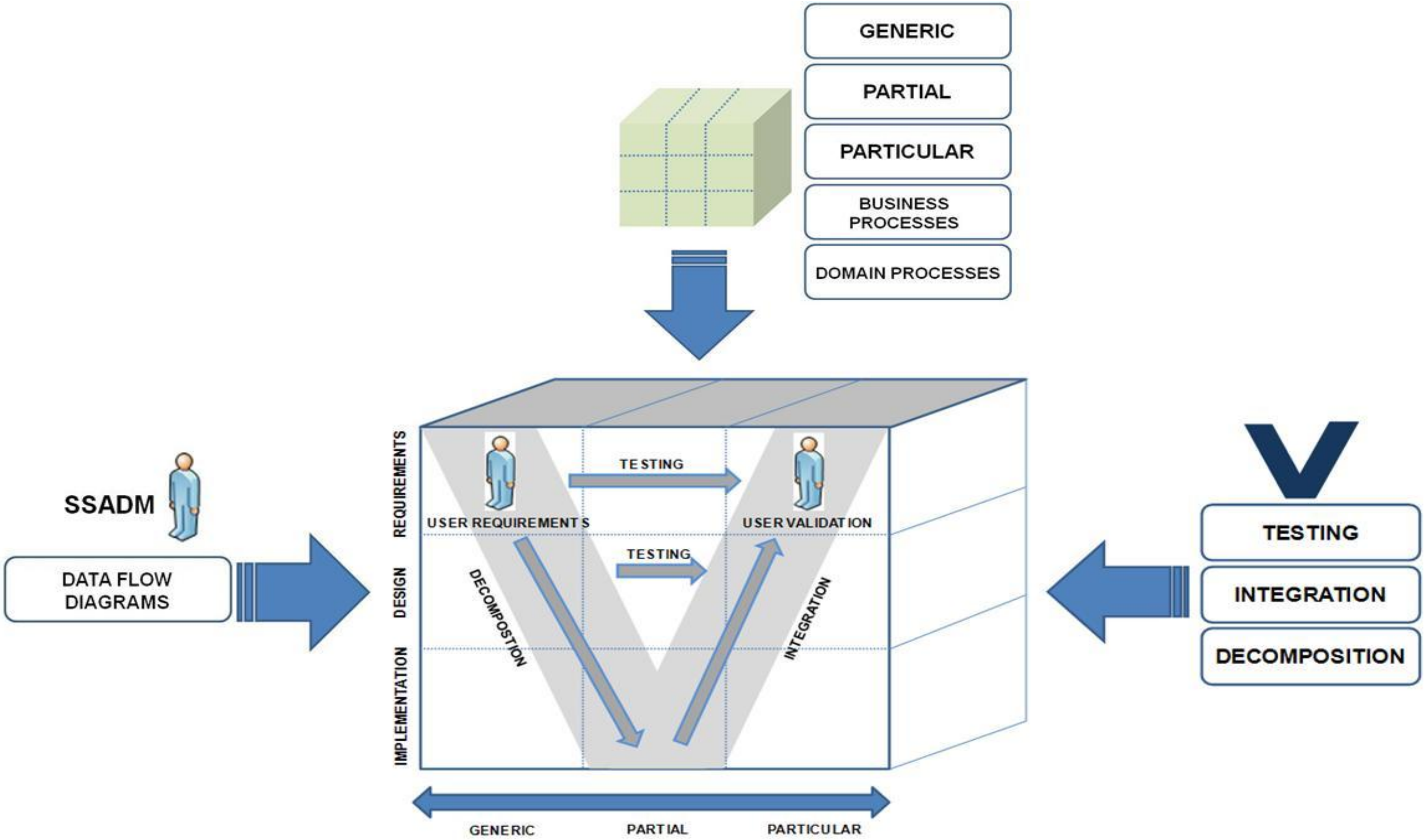


Figure 2.9 Combining elements from systems engineering process models and enterprise modelling techniques

2.4.8 Iterative design

The value of iterative design has been confirmed by several studies (Tan et al 2001, Bailey and Wolfson 2005 and LeDoux et al 2005). Each of these studies found that system modifications based upon the results of one test led to performance improvements on a follow-up test. The results indicated the following:

- A 28% faster average task completion time (Tan et al 2001).
- A 37% reduction in usability problems (Tan et al 2001).
- Nine of ten task scenarios took less time (Bailey and Wolfson 2005).
- User satisfaction score increased from 63 to 73 (Bailey and Wolfson 2005).
- The average time to complete task scenarios was reduced from 68 to 51 seconds- 25% improvement (LeDoux et al 2005).
- The overall user satisfaction score improved from 49 to 82- 67% improvement (LeDoux et al 2005).

The results from such studies highlight the importance of user requirement analysis, not just at the beginning of the design life cycle but throughout as an iterative approach. Developers need to understand the relationship between the user and product as the type of interface that provides the link between the technology and user, ultimately determines the usability of the product. In order to avoid this problem, a structured design process methodology needs to be followed which allows user input and re-iteration of requirements throughout from the hardware and software perspective. A methodology is referred to as a strategy for overcoming problems or barriers, it may consist of tools, techniques, conventions and documents to identify the necessary tasks, therefore a methodology is required to ensure the design process is thorough and considers all the elements that impact the system. Considering user types, requirements and varied interactions in relation to the current and proposed system from a hardware and software perspective is not an easy task (Bowman 2004).

Re-iteration of design, user requirements and the generation of prototypes to be evaluated are elements of the spiral systems engineering process model. The application of these elements to the proposed combined methodology is illustrated in Figure 2.10. Whether the developer is starting from the generic or particular level, it is suggested that the "vee" model is still applied across the requirement, design and implementation stage so that sufficient testing and user validation is achieved. The "re-iteration arrows" propose that if the system/product does not satisfy the client, the developer should revisit the user requirements and redefine all system and user requirements, to allow any changes to be identified. Although CIMOSA and SSADM constructs can be applied to both physical and logical systems, how data is presented to the user is not fully investigated using these constructs alone. Communication of the data is fundamental in supporting performance analysis, how the user accesses and interacts with software relates to another area of user centred design known as "user interface design".

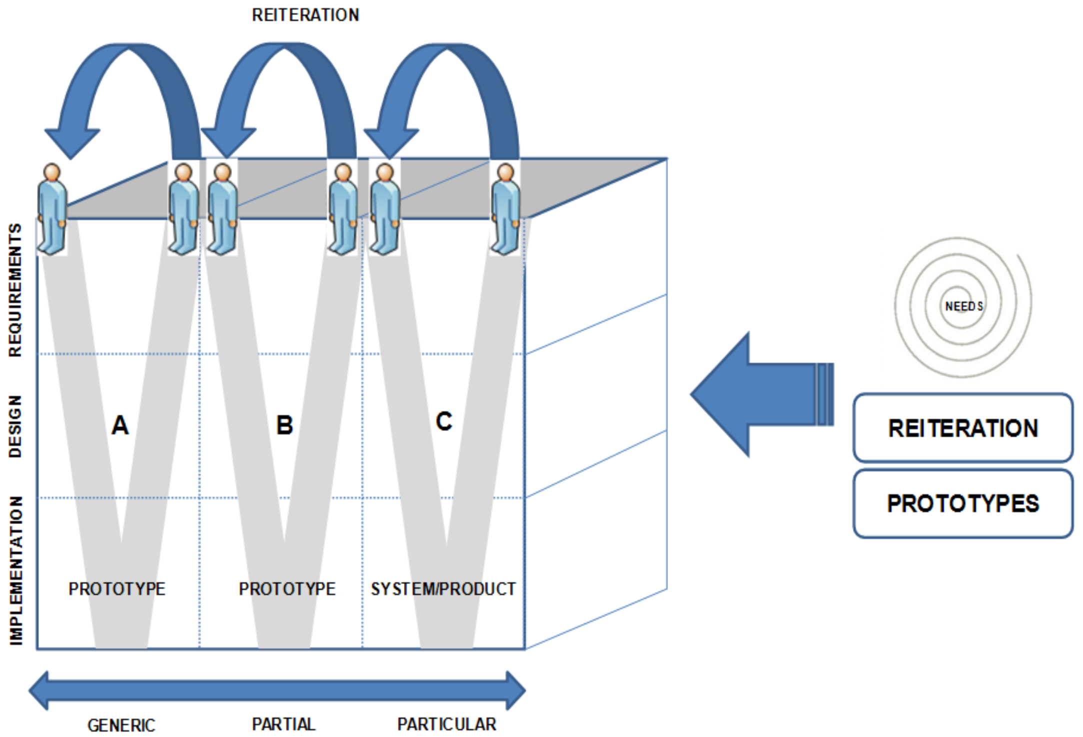


Figure 2.10 Applying the element of re-iteration to the combined modelling approach

2.5 User Interface Design

User interface design encompasses a variety of processes. The term interface is often used in reference to computerised technology, however, mechanical technology also has an interface with which users must interact (Galitz 2007). Therefore, the term "user interface design" needs to be considered from many perspectives. The variety of terms and the relationships between them are illustrated in Figure 2.11, whilst each element is discussed in further detail in Table 2.2.

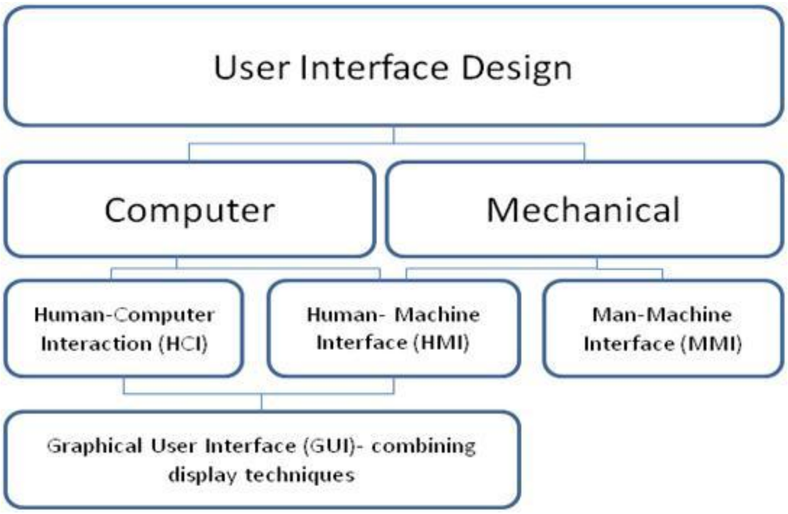


Figure 2.11 Overview of the terminology within user centred design and relationship between each

Term	Explanation
User Interface	The term is used generally in reference to both physical and logical design (hardware and software). It involves linking multiple forms of equipment and creating a logical integration between them. When referring to the user interface of a mechanical system, the term HMI is more commonly used.
Human Machine Interface (HMI)	Also known as Human Machine Interaction or Man-Machine Interface (MMI) where the human and the machine meet. It is the area of the human and the area of the machine that interact during a given task (Karat 1993, Bennett 1979).
Human-Computer Interaction (HCI)	The study of interaction between users and computers, still considered as HMI or MMI. HCI differs from HMI as the focus is on users working specifically with computers, rather than other mechanical devices
Graphical User Interface	A type of user interface that allows users to interact with programs other than typing, such as portable media players or gaming devices; household appliances. A GUI offers graphical icons, and visual indicators, as opposed to text-based interfaces, typed command labels or text navigation to fully represent the information and actions available to a user. The actions are usually performed through direct manipulation of the graphical elements. GUI uses a combination of technologies and devices to provide a platform the user can interact with, for the tasks of gathering and producing information (Davis 2008).

Table 2.2 A review of user interface design terminology

2.5.1 The Human-Machine Interface

The increased reliance upon computerised technology and electronic devices means that user interfaces are now an integral part of design in communicating data to the user. As technology has advanced, the terminology has broadened to accommodate the different elements that relate to the user interface. As demonstrated in Figure 2.11, the Human Machine Interface is a term used to refer to both computer and mechanical design, this is often confused with Human-Machine Interaction, which investigates how the user interacts with a system and aims to predict the navigation through software. Consideration of the Human-Machine Interface and Human-Machine Interaction needs to be investigated as they are two separate elements (Shackel 1991). The design of the interface relates to how data is presented to the user, whilst the interaction considers the navigation through the logical design and relationship with other physical components.

Figure 2.12 Example Human-Machine Interfaces commonly found in a gym environment

A majority of exercise system Human-Machine Interfaces provide information and guidance to the user during the configuration and exercise session (Smith 2007). Example Human-Machine Interfaces found in the gym environment are presented in Figure 2.12. Such functionality requires a combination of buttons and icons to enable the user to use the system "intuitively" without overloading the user with text. These systems commonly rely upon Graphical User Interfaces to increase usability of the system.

2.5.2 The Graphical User Interface

Designing within the sports domain to support performance analysis requires thorough analysis of the user types and likely interaction with the system. This ultimately determines the complexity and necessity of supporting software. With the nature of the resistance training research presented in this thesis being to support performance analysis, providing the functionality to view and analyse data is crucial. Space to communicate with the user in the gym environment is limited. Effective use of icons is a useful tool for maximising the space available, therefore is suggested that the development of a Graphical User Interface (GUI) is suitable for this research. The Graphical User Interface as identified in Table 2.2 is a type of user interface that allows for more interaction with a computer than typing alone. The current exercise systems presented in Figure 2.12 indicate that there is an increased reliance upon Human-Machine Interfaces (HMI's) to configure and review performance data during and post exercise, there is a general reliance upon Light Emitting Diodes (LED's) or Liquid Crystal Displays (LCD's). Rowing machines, cycles, elliptical trainers and treadmills are commonly found to utilise such inexpensive technology. With such a broad range of users in the gym environment, with different goals, levels of ability and motivation, the interface needs to be versatile in order to accommodate such a wide and varied user population. With the increase in advanced monitoring technology, the need to develop advanced interfaces has become a major requirement within sports monitoring.

GUI's are often composed of a collection of elements referred to as objects, these can be seen, heard, touched, or otherwise perceived. Objects are always visible to the user and are used to perform tasks and are interacted with as entities independent of all other objects. The user performs actions on the objects to achieve certain tasks which may include accessing and modifying objects by pointing, selecting or manipulating (Galitz 2007). However, developers need to consider the specific requirements of the interface to determine whether a GUI is appropriate.

How the data is displayed affects the user experience and can result in the rejection of the technology should the process become too complex. It is expected that the user will be required to "learn" the system to some degree, however, reducing the complexity of tasks and considering their navigation through the system, may reduce the learning time. The usability of the system needs to be considered, for example, should the terminology throughout the system be inconsistent, usability is reduced. Designing an "intuitive" interface is dependent upon the usability, therefore, promoting usability is crucial in determining the success and acceptance of a system. The concept of usability and varied views on promoting usability are discussed in the following section.

2.5.3 The concept of usability

The most commonly held view is that usability is a quality attribute that assesses how easy a user interface is to use. The term usability also refers to methods for improving ease-of-use throughout the entire design process (Bennett 1979). A more formal definition has been proposed simply defining usability as the capability to be used by humans easily and effectively (Shackel 1991). Although not all usability research is conclusive due to the variety of proposed concepts and subjective assessment of usability, some statistics do exist. Usability engineering has demonstrated reductions in the product-development cycle by over 33-50% (Bosert 1991) whilst, systems design with usability engineering has typically reduced the time needed for training by approximately 25% (Landauer 1995). Furthermore, 80% of all software development costs occur after the product has been released (Shackel 1991). Previous research also investigated the effect of improved screen clarity by making the appearance less "busy", results showed that the users were approximately 20% more productive (Galitz 2007). These statistics demonstrate the impact a detailed, well researched design process can have. Other research has focused on identifying the elements that construct a "usable" system, however, the subjective nature of the area inhibits the clarification of necessary components. To tackle this ambiguity, an analysis of research relating to common GUI user defined problems, their causes and the current views upon avoiding these problems is discussed in the following section.

2.5.4 Promoting usability in GUI design

One study found users spend almost 40% of their computer time overcoming problems such as tackling difficult installations, viruses, and connectivity troubleshooting (Ceaparu et al 2004). Common problems experienced by users have been reported by IBM specialists, the top ten results are shown below (Galitz 2007).

PROBLEMS	CAUSES
• Ambiguous menus and icons and unclear step sequences.	• Lack of early analysis and understanding of the user needs.
• More steps to manage the interface than to perform tasks.	• A focus on using design features or components that provide 'novelty' value.
• Highlighting and selection limits. • Inadequate feedback and confirmation. • Input and direct manipulation limits.	• No usability testing. • Little or no creation of design element prototypes.
• Lack of system anticipation and intelligence. • Languages that permit only single-direction movement through a system the user cannot retrace their steps.	• No common design team vision of user interface design goals. • Poor communication between members of the development team.

Table 2.3 A review of common problems and likely mistakes that occur during GUI design (Galitz 2007).

Such studies have identified the need to establish what constitutes a "usable" system. Previous research has outlined five components to promote usability as identified in Figure 2.13 (Shackel 1991, Schneidermann et al 2004). Of these elements, consistency was identified as the most important due to the potential application to many aspects of design (Schneidermann et al 2004). Good user interface design involves creating a set of consistent expectations and then meeting those expectations, however, finding the balance between consistency and flexibility is a difficult task. Flexibility is key to accommodating a large user population whilst consistency is crucial to improving the user experience and enhancing the overall usability of the interface. One user does not represent all and prediction of user behaviour is a difficult task. The more flexible a system is, the more likely a user's needs will be accommodated. However, differing views regarding which elements should be consistent whilst still targeting a variety of user types means that a reduction in consistency is sometimes unavoidable. This is supported by research in which it is suggested that as the level of customisation increases, the level of usability decreases (Smith 2007). Therefore, developers must identify which processes within the system can be "shared" or likely to be completed by all or most users and differentiating these from processes that are more specific to particular users (customised aspects).

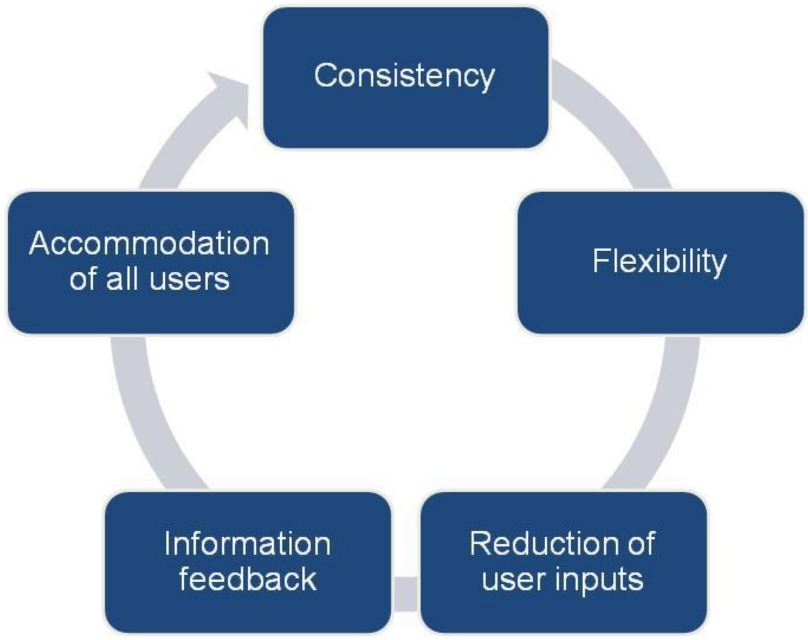


Figure 2.13 Five components to increase usability (Shackel 1991, Schneidermann 2004).

A summary of this research is given in Table 2.4. The components identified by numerous researchers share the same goals but have used different terminology. For example, the component of consistency (Schneidermann 2004) relates to the need to improve the learning process (Galitz 2007), whilst the efficiency of the design relates to the intuitive nature of the interface. Although, the techniques identified promote effective design, each system has individual requirements; therefore the challenge is adapting the techniques to each application. Usability of the system can be further improved by considering the navigational path and user interaction, whether there is a distinction between users will determine the number of inputs, whether there is logical progression and overall consistency. Investigating Human-Machine Interaction is discussed in the following section.

Common mistakes	Subsequent design flaws	Avoiding common mistakes
• Lack of early analysis and understanding of the user's needs. • A focus on using design features or components that provide "novelty" value. • Little or no creation of design element prototypes. • No usability testing. • No common design team vision of user interface design goals. • Poor communication between members of the development team.	• Ambiguous menus and icons. • Languages that permit only single-direction movement through a system- the user cannot retrace their steps. • Input and direct manipulation limits. • Highlighting and selection limits. • Unclear step sequences. • More steps to manage the interface than to perform tasks. • Complex linkage between and within applications. • Inadequate feedback and confirmation. • Lack of system anticipation and intelligence. • Inadequate error messages, help, tutorials, and documentation	• Promote consistency • Promote flexibility • Reduce of user inputs • Provide Information feedback • Accommodation of all potential users • Effective design • Efficient design • Engaging design • Error tolerant • Easy to learn • Memorable design • Promote user satisfaction

Table 2.4 A summary of common GUI design mistakes and methods to avoid them (Galitz 2007).

2.6 Human-Machine Interaction

The interface design and user interaction are dependent upon one another, modelling this interaction can help identify the navigation of the software. HMI modelling employs a "storyboarding" technique which aims to view the system in relation to three levels of granularity (Breen 1998, Lin 1999, Lank et al 2000, Mellor 2006, Crnkovic 2003).

1. End User HMI's comprise of one or more HMI Tasks,
2. HMI Tasks support HMI functionality,
3. HMI widgets provide the functionality to interact with the end user.

Using the domain classifications as the foundation of the basic GUI structure and business process analysis to distinguish the order of tasks, the developer can use a method of HMI tasks and widget storyboarding to investigate the navigation of the system and how the user will interact with the interface. This is an important design process as it refers back to the user requirements and causes the developer to focus on reducing the number of HMI tasks the user needs to complete before accomplishing their need.

Consequently, the less tasks a user needs to complete before their need is met, the more usable and desirable the system is. Consideration of the different user types is fundamental to this process, as mapping the navigational path specific to the user increases the usability of the system. This further supports the need for a combined approach as CIMOSA or SSADM techniques do not distinguish between different navigational paths. Storyboarding improves communication between developers and users, the reliance on visual information and ability to decompose a particular task step by step reduces likely misinterpretation between the user and developer. Furthermore, it provides a method of testing how a user would intuitively navigate through a system in order to complete a task. These tasks are determined by the identified user requirements. Hence this process is heavily dependent on user input and definition of user requirements. In a similar way to the “vee” model, each user widget must originate from a user requirement otherwise the interface becomes “cluttered” with unnecessary icons and functions. Decomposition of interface use into HMI tasks encourages the developer to decompose the system, making this method applicable to the proposed combined methodology.

2.7 Proposed combined modelling approach

The combined methodology incorporates the “vee” model, CIMOSA and SSADM elements that encourage the developer to view the system as a whole, identify user requirements according to user type and level, decompose the overall system into subsystems and consider the relationship and data flow between each. Throughout this process a transition is made from a generic (broad) to particular design (narrow) which can accommodate numerous iterations of the system. The flexibility of the methodology is reinforced by the application to both hardware and software design. How performance data is collected, stored and communicated are the three main elements to this research, therefore considering the software usability is a key component of the methodology. Consequently, the final proposed methodology incorporates the use of HMI storyboarding should the developer require supporting technology.

Overall, the methods employed follow a proposed step by step framework using a combined approach of modelling techniques that enables reiteration of the user needs throughout the hardware or software design process. Effective translation of end user business needs into system requirements is necessary for the success of any system. In the absence of customer oriented requirements, any system is likely to be rejected by the end user. Recent research also outlines the importance of user type and level or experience, as an increasing number of software users are non expert (Smith 2007), placing new demands on the software. Furthermore, the "typical" user of a system does not exist, the requirements of an individual user usually change with experience (Mackey 2009).

STEP	AIM	MODEL/MODELLING TECHNIQUE	REASON
1	**Define objectives**	SSADM	Encourages developer to view system as a whole
2	**Define user requirements**	"vee" process model Spiral process model	User input is obtained in the early stages
3	**Feasibility testing**	SSADM "vee" process model	System capability set is identified in the early stages. The testing is broken down into subsystems.
4	**Systems analysis**	CIMOSA SSADM "vee" process model	Current user interaction and system behaviour is investigated
5	**Domain classification**	CIMOSA SSADM "vee" process model	Subsystems within the system are identified using the previous step and categorisation- aiding decomposition.
6	**Business process analysis**	CIMOSA SSADM "vee" process model	Each subsystem is further decomposed in relation to user requirements
7	**Consolidation of the subsystems and design generation**	"vee" process model	Integration of the system begins again, testing and user validation is used to evaluate success.
8	**HMI task analysis (software)**	HMI storyboarding "vee" process model SSADM	User requirements regarding user interaction and tasks to be performed are identified. Decomposition of the system.
9	**Consolidation of HMI tasks (software)**	HMI storyboarding "vee" process model	Integration of the system presents the system as a whole, testing and user validation is used to evaluate success.

Table 2.5 A list of the different techniques that form the proposed combined methodology

Generic assumptions about skilled domain users being the primary users limits the intuitive nature and usability of these systems, instead knowledge about the problem domain, communication processes and the communication agent needs to be acquired and this can only be done by considering different user types and their likely interaction with the system (Dix et al 1991). Consequently, this combined approach forces the developer to revisit both the user type and user needs at the particular and partial level. A summary of the methodology is listed below in Table 2.5, whilst the application of the steps to increase the methodology flexibility in relation research focus first identified in Chapter 1 is illustrated in Figure 2.14.

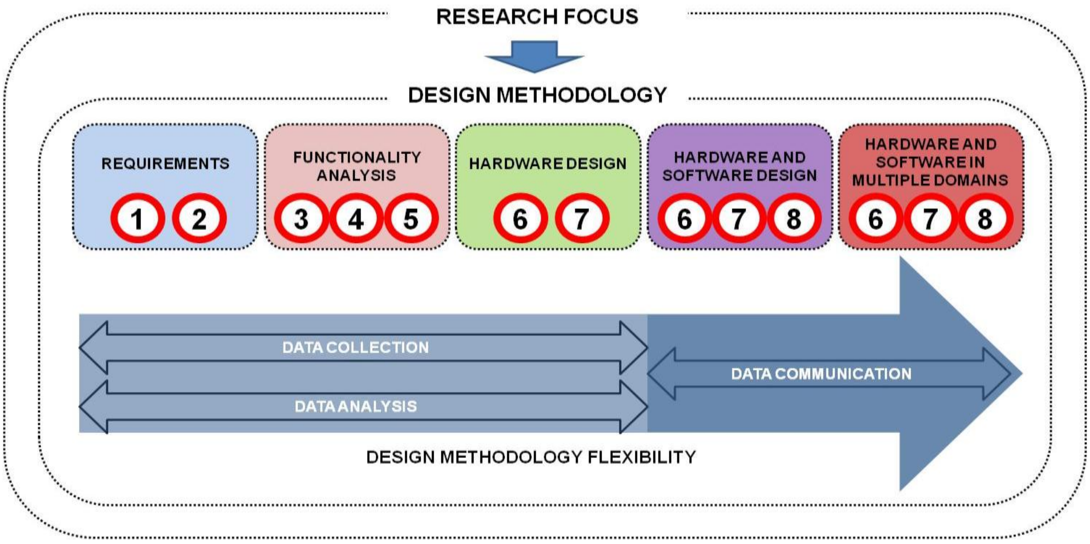


Figure 2.14 Application of the methodology steps to the original research focus to increase flexibility of the design process.

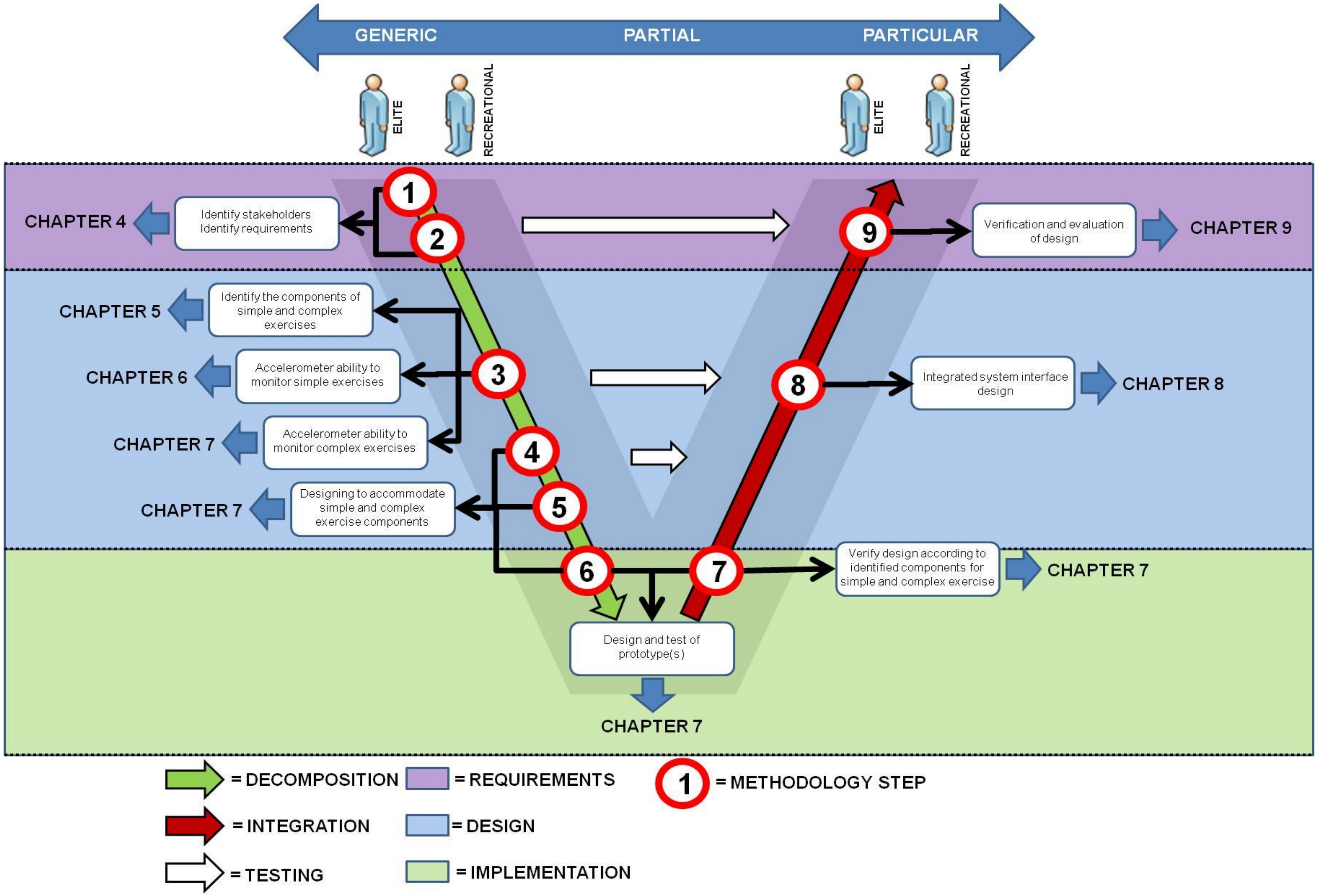


Figure 2.15 Proposed user-centred design process that allows re-iteration of the user needs

2.9 Brief Chapter summary

TARGET OBJECTIVE:

Design and implement a combined and flexible systems modelling approach that supports user-centred design to be applied to the resistance training domain.

TARGET RESEARCH QUESTIONS:

Which modelling techniques promote user-centred design?

One of the most commonly used enterprise modelling techniques is CIMOSA due to the modelling flexibility. CIMOSA enurorages decompositon of requirements through domain classification and business process analysis. Systems analysis modelling is used to decompose systems and to gain an understanding of the data flow within a system. Although a less researched form of modelling, HMI task analysis and storyboarding enables user interaction with the system to be considered. With the growing reliance upon interfaces to communicate data, how the user interacts with the system is a fundamental aspect of user centred design. These modelling techniques consider user centred design from a hardware and software perspective.

Which system process models promote user-centred design?

The “vee” model promotes decomposition of the requirements before integration can occur ensuring that every design requirement is derived from a user requirement. Therefore the whole process is centred around the user. The element of requirement re-iteration is supported by the spiral process model allowing the design to migrate with user requirements which are subject to change. This flexibility also accomodates protype generation, supporting testing required to understand the capability of the product.

How should the modelling techniques and system process models be combined to provide a user-centred research and design methodology?

The iterative, flexible and systematic elements of the modelling techniques and process models were combined to promote user centred design. Defining user requirements in the early stages using the “vee” model approach ensures user input is integrated and all design requirements originate from user requirements. Combining the overall CIMOSA reference architecture ensures that the developer considers the system from a broad perspective and collects the relevant information to narrow the design process at the particular level. Selecting SSADM techniques that relate to the CIMOSA architecture and “vee” model ensures that decomposition and consideration of all the subsystems is achieved. The inclusion of SSADM techniques supports the combination of CIMOSA and “vee” model functionality. User-centred design is further incorporated through the consideration of HMI storyboarding to ensure the software design can be fully decomposed and integrated using a visual technique. In relation to the original objective highlighted at the beginning of the Chapter it is suggested that by identifying the elements that are shared amongst different modelling techniques and disregarding the elements that inhibit user centred design, combining methods can promote user-centred design for both logical and physical systems. A summary of the new knowledge acquired as a result of the chapter research in relation to the core questions identified in Chapter 1 is presented in Figure 2.16.

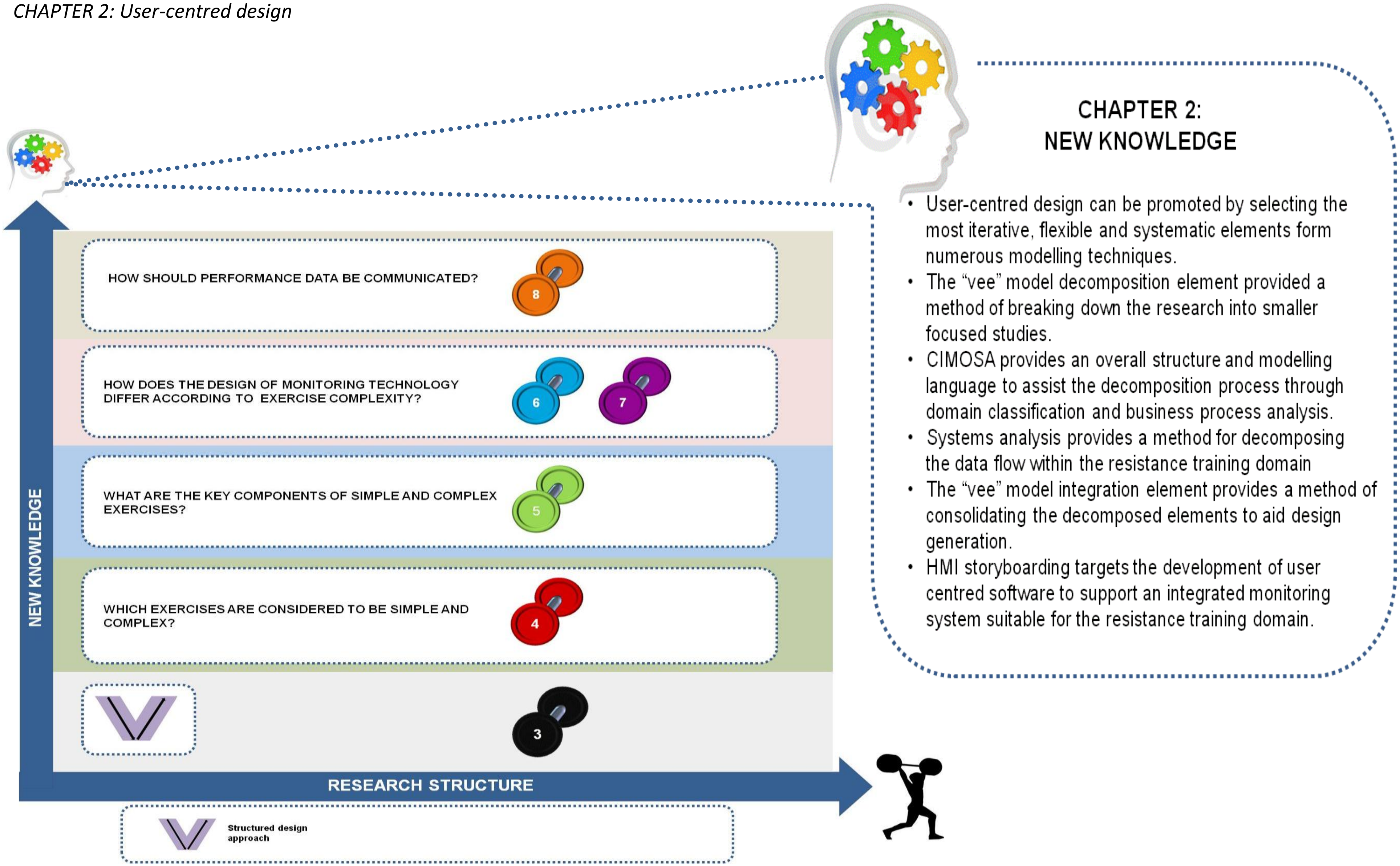
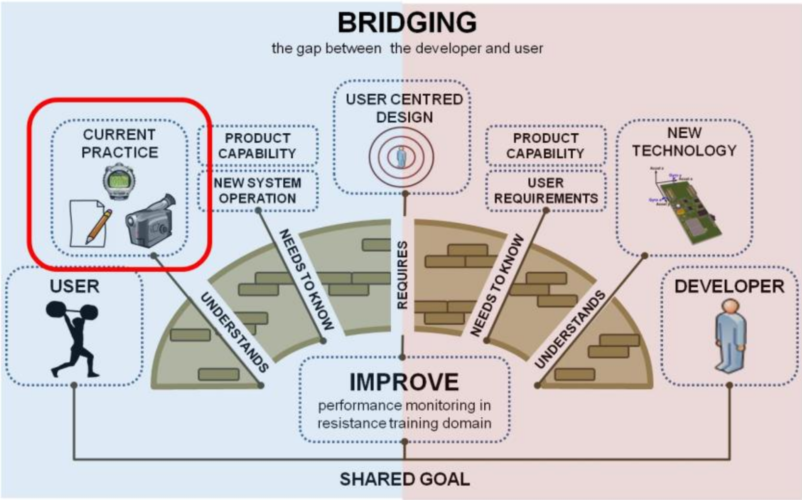


Figure 2.16 The identification of new knowledge acquired as a result of the Chapter: The structured "vee" model methodology



Chapter 3

3.0 Literature review

TARGET OBJECTIVES:

- *Gain an understanding of exercise physiology to understand the effects of resistance training.*
- *Identify training inputs and outputs and determine which are most relevent to the resistance training domain.*
- *Identify the current monitoring techniques used within the resistance training domain and investigate the benefits and limitations of each.*
- *Identify the current gaps in research and technology development in the resistance training domain.*

3.1 Introduction

In order to apply the methodology designed in Chapter 2 there is a need to establish the requirements and needs within the resistance training domain. An understanding of the current practice was required to further promote user-centred design. Therefore, a literature review of research and current practice within the resistance training domain is documented in this Chapter. The numerous target objectives demonstrate the need to investigate several areas of the resistance training domain. These areas are identified in Figure 3.1 in which the performance monitoring cycle within the resistance training domain is presented. The supporting software and graphical user interface communicate performance data to the user, these elements were discussed in Chapter 2. The performance data communicates the effects of the resistance training and influences the training inputs. The training outputs are monitored by a range of technologies which are then communicated by the GUI to begin the cycle again. The effects of resistance training, the relationship between with the training inputs and outputs and how the training outputs are monitored is investigated in this Chapter. The separation of the literature review into four sub-categories is illustrated in Figure 3.1.

1. General exercise physiology is investigated to provide an understanding of the relationship between human movement and muscular contraction.
2. The types of training inputs required to design a training program are investigated to identify those of highest relevance to the resistance training domain.
3. The types of training outputs often monitored in the resistance training domain are identified to determine which received most research focus.
4. The technology currently used to monitor the training outputs is investigated to determine whether there is a need to improve resistance training research and development of performance monitoring technology.

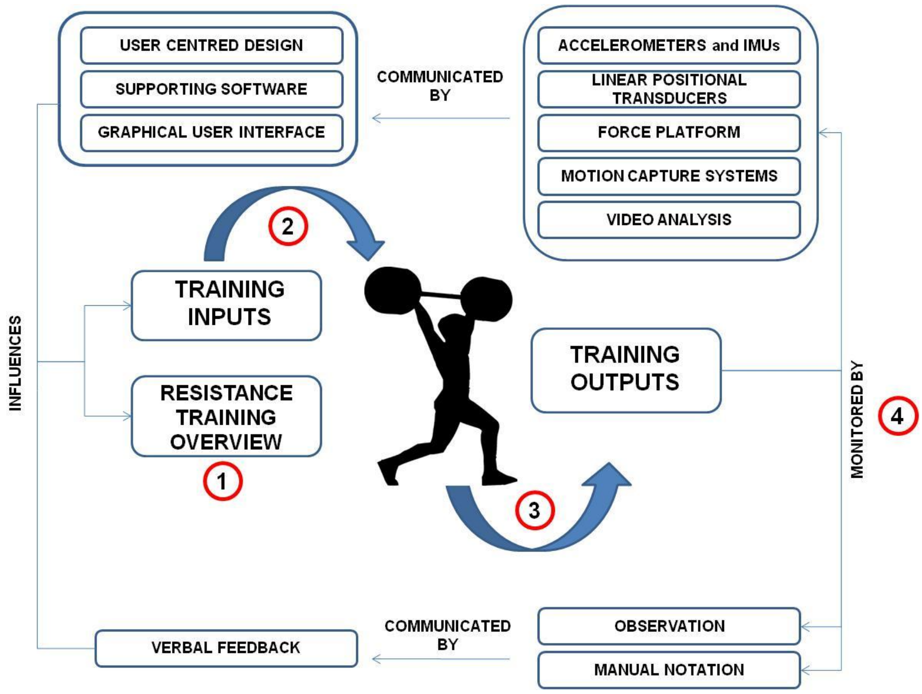
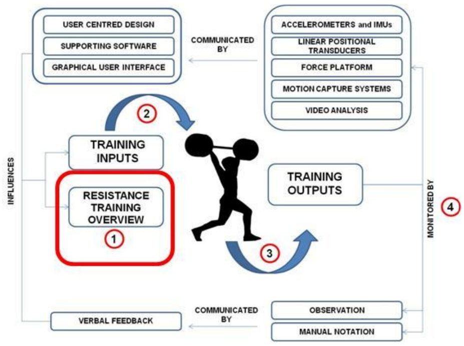


Figure 3.1 The performance monitoring cycle within the resistance training domain and identification of the literature review sub categories



3.2 Section 1: Resistance training overview

TARGET RESEARCH QUESTION:

What are the benefits of free weight resistance training and what types of adaptation occur as a result of resistance training?

Health and fitness are often mistaken to mean the same thing, however distinction between the two is crucial when designing both technology and training programs to target the user types and requirements. Health is a state of complete mental, physical and social well being, whilst fitness is the ability to meet the demands of a physical task (BrianMac 2010). The health related aspect is an area of major concern for the government. Results from 2006-2007 indicate that poor diet-related ill health cost the NHS in the UK £5.8 billion, the cost of physical inactivity was £0.9 billion, whilst obesity cost £5.1 billion (Scarborough et al 2011). Public health guidelines focus on the promotion of physical activity and aerobic exercise (Winett 2001). However, research has shown that resistance training can promote health gains (Feigenbaum 1999), whilst having an effect on balance and muscle mass that can prevent and reduce the effects of osteoporosis (Layne 1999). Both scientific and medical communities recognise that muscular strength is a fundamental physical trait necessary for health, functional ability and an enhanced quality of life (American College of Sports Medicine (ACSM 2002).

Resistance training is also heavily used within the sporting domain to improve muscular fitness and resultant sporting performance. Research has shown that effective resistance training can have a positive effect on numerous fitness variables such as muscular strength, power, hypertrophy (muscle size increase), local muscular endurance, speed, balance, coordination, jumping ability and flexibility (Rutherford and Jones 1986, Adams and O'Shea 1992 and Delecluse et al 1995). Such findings have encouraged health organisations to promote the use of resistance training in overall fitness programs and sports specific training (Winett 2001).

Resistance training is known as strength or weight training. Due to the numerous health and fitness benefits, it has become one of the most popular forms of exercise (Fleck and Kraemer 2004). There are a number of terms often used in the same context as resistance training each describing an exercise that requires the muscles to overcome an opposing force (Fleck and Kraemer 2004). Resistance training is used as a general term to describe training with different modes using both free weights and machines. This training may be applied to different domains such as rehabilitation and injury prevention, general fitness, recreational activity and bodybuilding (Fleck and Kraemer 2004). The general terms used to refer to resistance training are identified in Figure 3.2.

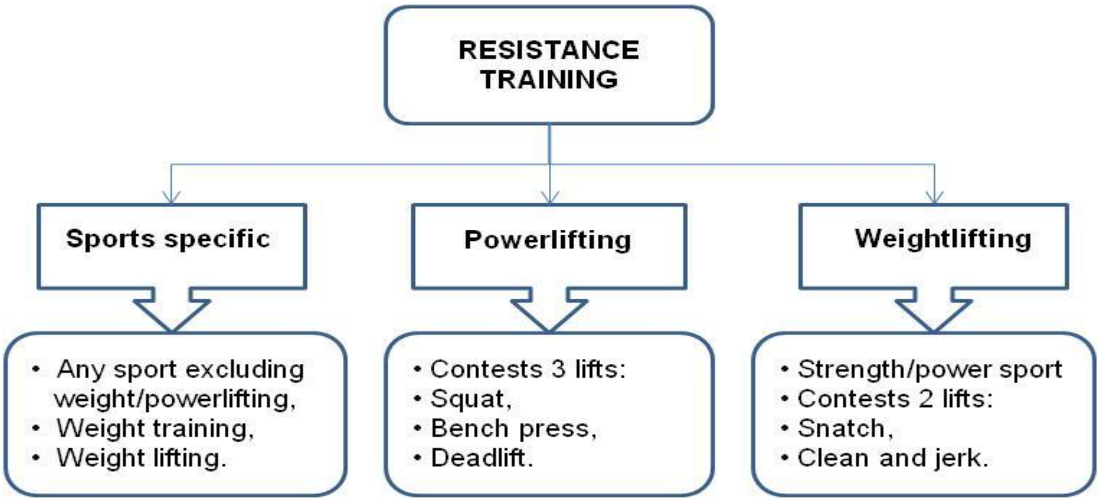


Figure 3.2 The difference terms associated with resistance training

Resistance training can involve the use of resistance machines, pulleys or free weights. Machines have been regarded as safer to use and easier to learn (Foran 1985) as they can aid stabilisation of the joint and prevent misalignment during the execution of the exercise. However, free weights develop inter and intra-muscular coordination that increases the ability to replicate a specific task or skill (ACSM 2002). Furthermore, a study conducted by McCaw et al (1994) demonstrated that deltoid muscle activity was significantly greater in a free weight bench press than in a machine bench press due to the difference in stabilisation required. It is therefore suggested by the ACSM that novice and intermediate training should include both machine and free weight exercises, whilst advanced training should focus upon free weight exercise (ACSM 2002).

Machines constrict range of motion and simplify the movement, with the result that less feedback is required to execute a particular exercise. Alternatively, free weight training requires more body control and increased feedback is required to execute exercises efficiently without causing injury. Free weight training varies in complexity, movements that only require the movement of one joint (isolated exercises) are easier to learn and execute than multi-joint actions (compound exercises). Consequently, an Olympic lift (compound exercise) which requires extensive whole body movement is more difficult to learn than an isolated exercise such as the bicep curl. Therefore, the type and extent of feedback required also depends upon the type of exercise. Many types and variations of free training exercises exist. An overview of common lifts and exercises are identified in Figure 3.3. This is not an exhaustive list but has been categorised according to elite coaching input, interview and questionnaire data investigating the perception of exercise execution complexity discussed in Chapter 4.

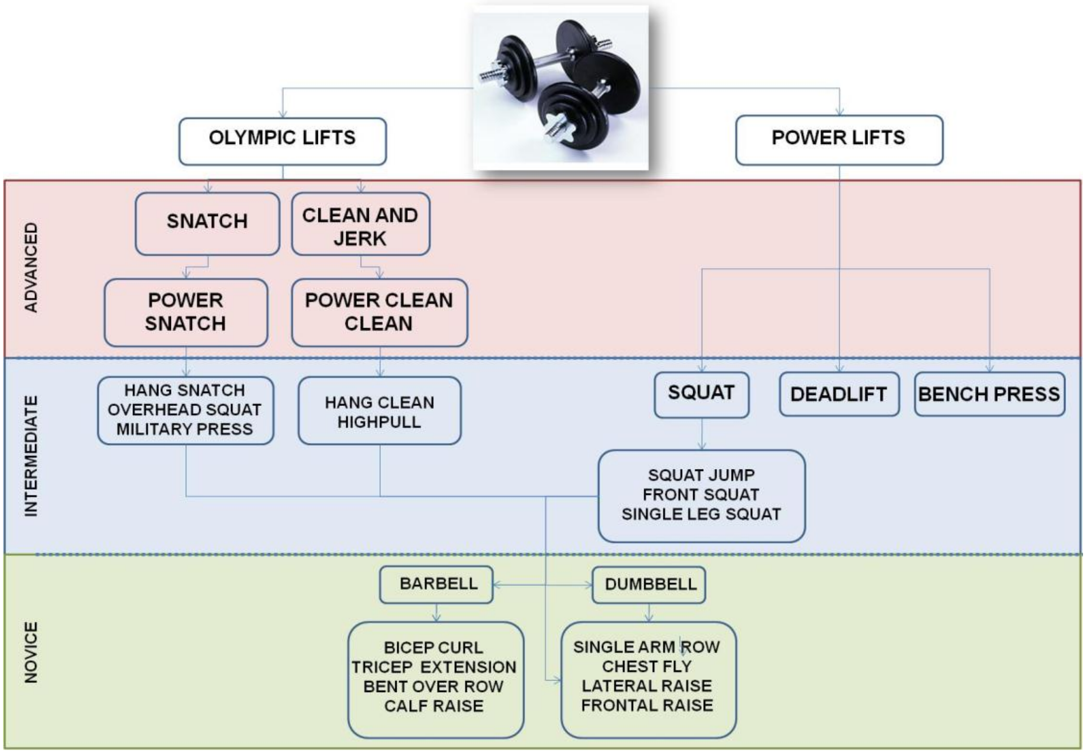


Figure 3.3 Classification of common free weight training exercises according to the complexity

The exercises are categorised as either advanced, intermediate or novice based upon the level of experience and coaching input required to learn and execute each one. Regardless of the complexity of the exercise, the ability to provide feedback in the free weight training environment during a session is currently heavily reliant upon qualitative input. Qualitative analysis applies the basic principles of mechanics to performance skills and therefore bases scientific principles on subjective observation (Lees 2002).

Qualitative analysis is defined as "systematic observation and introspective judgement of the quality of human movement for the purpose of providing the most appropriate intervention to improve performance" (Knudson and Morrison 1997). At the advanced level, qualitative feedback is readily available, however, once an individual is highly skilled, the need to combine quantitative analysis increases. At the advanced level where coaching is essential, quantitative feedback may be gained through post session analysis. This feedback will differ greatly from the type of feedback required at the novice level where simple exercises are being executed. At the novice level, the current ability to gain performance feedback is limited. A training partner may provide the only form of quantitative input. The knowledge required to structure training and adapt training inputs (i.e sets, repetitions (reps) and load) is not necessarily abundant at the novice level. In order to understand the effects of resistance training and resultant training inputs and outputs, an understanding of body movement, muscle physiology and training principles is required. A basic review of human movement and muscle physiology is given in the following section.

3.2.1 Human movement

Various terms exist to describe human movement in relation to the three mutually perpendicular intersecting planes. It is within these planes that all joint movements occur (Bartlett 2007). The three planes are known as the sagittal, frontal and horizontal planes, collectively referred to as the cardinal planes. Movements about a joint are predominantly rotational, taking place perpendicular to the plane in which they occur, this is known as the axis of rotation (Bartlett 2007). The three axes are defined by the intersection of the three planes, the terms being the sagittal, frontal and vertical axes. Describing a gross movement is often achieved by referring to the dominant plane. However, the individual joints may be working within several different planes, referred to as multi-planar motion (McGinnis 1999). Multi-planar movement is easier to achieve using free weights as opposed to resistance machines, which supports further the ACSM encouragement of free weight use. A review of dominant motions within each plane, axes and example movements is outlined in Table 3.1. (McGinnis 1999 and Bartlett 2007). Understanding the different types of motion and the planes in which they occur allows training programs to be designed that target specific muscles whilst replicating a desired movement. How muscles achieve movement is discussed in the following section.

Plane	Description	Axis	Description	Motion	Example
Sagittal	A vertical line extending from the posterior to anterior, dividing the left and right sides of the body. Also known as the anteroposterior plane.	Frontal	Passes horizontally from left to right, formed by the intersection of the frontal and horizontal planes.	Flexion/ Extension	Walking, running, overhead press.
Frontal	A vertical plane that extends from left to right, dividing the body into anterior and posterior halves. Also known as the coronal plane	Sagittal	Passes horizontally from posterior to anterior, formed at the intersection between the sagittal and horizontal planes.	Abduction/ Adduction, Side flexion, Inversion/ Eversion.	Star jump, lateral arm raise.
Horizontal	This plane divides the body into top (superior) and bottom (inferior) halves. Also known as the transverse plane.	Vertical	Passes vertically from superior to inferior, formed by the intersection of the sagittal and frontal planes.	Int/ext rotation, Horizontal flexion/ extension.	Throwing, golf swing.

Table 3.1 Relationship between the planes and axes and example movement

3.2.2 Muscular contraction

The ability of the neuromuscular system to generate force is necessary for all types of movement. This force can only be generated through contraction of the muscle (ACSM 2002). This contraction can be voluntary or involuntary, depending on the type of muscle tissue and resultant role. There are three different types of muscle tissue**.**

Skeletal muscle: Responsible for movement

Cardiac muscle: Responsible for pumping blood around the body

Smooth muscle: Responsible for sustained contractions in the blood vessels

Skeletal muscle causes human movement and therefore enables resistance training to occur. To understand how muscular contraction occurs, the physiology of skeletal muscle illustrated in Figure 3.4. Each muscle body consists of multiple muscle bundles which contain muscle fibres. These muscle fibres can fall into one of three categories displayed in Figure 3.4.

Within the muscle fibres are a large number of myofibrils, each constructed of linear sarcomeres. The sarcomeres contain two contractile proteins; actin and myosin (Jones and Round 1990), according to the most popular and accepted theory. It is these proteins that are fundamental to muscular contraction. This theory is known as the "sliding filament theory" (Billeter and Hoppeler 1992) and is based on a chemical process referred to as a "cross bridge cycle". Muscle fibres contract through shortening of the myofibrils which occurs as myosin uncouples from the actin, reattaches, creates movement and then detaches. This cross bridge cycle is dependent on chemical and neurological signals which stimulate the process (Clark and Lucett 2011).

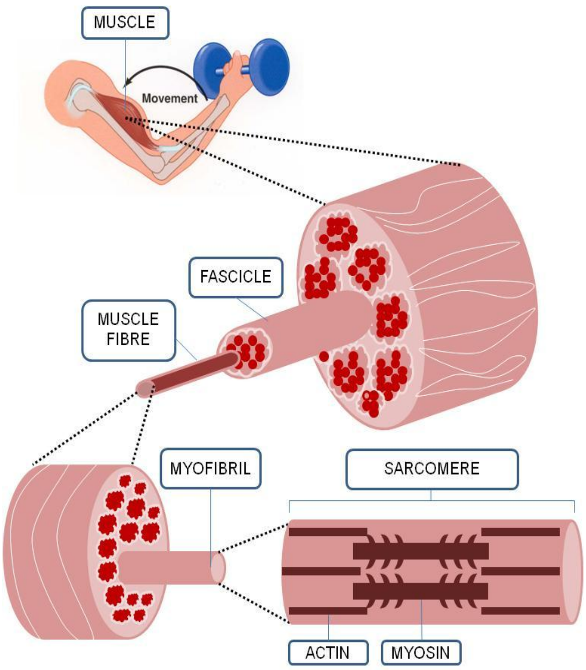


Figure 3.4 Muscle anatomy

Fibre type	Characteristics	Sport
Slow Oxidative (SO)	Smallest in diameter Least powerful Dark colour due to high concentration of myoglobin Fatigue resistant	Long distance running
Fast Oxidative-Glycolytic (FOG)	Intermediate in diameter Contain high amounts of myoglobin and many capillaries Dark in appearance Higher contraction speed than SO fibres	Team sports
Fast Glycolytic (FG)	Largest in diameter Contain highest concentration of myoglobin Most powerful contractions White in colour due to low myoglobin concentration Respond well to hypertrophy training (increased muscle size)	Sprinting, weightlifting

Table 3.2 Muscle fibre type classification

The contraction of a skeletal muscle can fall into one of three categories; Isotonic, Isokinetic and Isometric (Clark and Lucett 2011). Isotonic and Isokinetic contractions can be further divided into concentric and eccentric contractions. Individual or multiple contractions can occur that may cause movement of one or multiple joints. Single joint movement is referred to as an isolated exercise, whilst multi-joint movement is referred to as a compound exercise. The ability of a muscle to contract eccentrically and concentrically allows muscles to work in pairs. Therefore, as one muscle shortens, the other lengthens, allowing movement at the joint to occur. As a result, a muscle can also be described as working agonistically or antagonistically depending on which muscle is causing the movement. An overview of contraction categorisation is presented in Figure 3.5. The agonistic relationship is represented by flexion and extension of the elbow which requires the biceps and triceps to work as a pair.

3.2.2.1 Rate of force development (RFD) and rate of power development (RPD)

The rate of force development (RFD) has been defined as the rate of rise of contractile force at the beginning of a muscle action (Aagaard et al., 2002). It has been suggested that the rate of force development is dependent on both a short and long component of the stretch shortening cycle (SSC) (Schmidtbleicher 1992). The short component is characterised by small angular displacement of the ankle, knee and hip joints, occurring within 100-250 milliseconds of lower body muscle activation. The long component occurs more than 250 milliseconds after muscle activation, involving larger angular displacement of the lower body (Schmidtbleicher 1992). Research conducted by Jenson, Flanagan and Ebben (2008) indicated that the rate of force development value is influenced by the inclusion or exclusion of the long component (>250 milliseconds). Therefore the speed of the measured exercise must be considered to determine whether the muscle activation and contraction will fully occur within the first 250 milliseconds of muscle activation.

RFD is calculated by dividing the peak force by the time to peak force, therefore, the higher the peak force and the lower the time to peak force the higher the rate force development. Rate of force development is crucial to power training due to the force-velocity relationship. The goal of power training is to increase the rate of force development and velocity of muscle contraction. The rate of power development (RPD) is calculated by dividing the peak power by the time to peak power. Increasing the peak power, reducing the time to peak power or achieving both, produces a higher RPD value. Explosive resistance training increases the slope of the early portion of the force time curve (maximum rate of force development). Although heavy resistance training increases maximum strength, the highest point of the force time curve, this type of training does not improve power significantly as maximal power is produced at intermediate velocities of movement, that is, at approximately 30% of maximum shortening velocity (Newton and Kraemer 1994) and (Schmidtbleicher 1985). Therefore, when devising training programs to increase power, the relationship between force and velocity must be considered to ensure that training velocity is not inhibited by the training load.

The force a muscle can generate depends upon both the length and shortening velocity of the muscle. The length-tension relationship refers to the strength of an isometric contraction and the length of the muscle at which the contraction occurs. Greatest force is generated when muscles operate closest to their resting length, when stretched or shortened beyond this, maximum force generation decreases (Gordon, Huxley and Julian 1966). The decrease in force is initially small, declining rapidly as the length deviates further from the resting length. The speed at which a muscle changes length also affects force generation. Force declines in a hyperbolic fashion relative to the isometric force as the shortening velocity increases, eventually reaching zero at some maximum velocity. This is referred to as the force-velocity relationship. This relationship significantly affects the rate at which muscles can perform mechanical work (power). As power is a product of force and velocity, the muscle generates no power at either isometric force (due to zero velocity) or maximal velocity (due to zero force). The optimal shortening velocity for power generation is approximately one-third of maximum shortening velocity (Brooks, Fahey and White 1996).

Rate of force and power development are both influenced by intra and inter-muscular coordination, therefore the ability to exert force and resultant power is affected by neural factors (Young 1991) and (Schmidbleicher 1985). Intra-muscular coordination is dependent on the extent of motor unit activation and is determined by muscle recruitment, the firing rate of the motor units, the synchronicity of the firing pattern and the stretch reflex. Inter-muscular coordination refers to the coordination between muscles and muscle groups and is influenced by activation of synergists and the co-contraction of antagonists. Inter-muscular coordination is required to develop a skill, training loads and velocity must be specific to the type of activity. Rate of force and power development is therefore specific to the activity, can be influenced by the level of skill required and may be used as an indicator of skill level and experience (Young 1993). Within the sporting domain, RFD and RPD are often calculated with standardised tests such as a counter movement jump (CMJ) or vertical jump. This allows coaches to evaluate and compare the potential of athlete's regardless of the skill level. A performance monitoring system that accommodates standardised testing of RFD and RPD would provide useful information at an elite and recreational level.

3.2.3 Human movement and muscular contraction summary

- Resistance training can achieve both health and fitness gains and is widely used within a competitive lifting, sports training and health related environment.
- Understanding the plane (sagittal, frontal and horizontal) and corresponding axis (sagittal, frontal and vertical) is crucial in determining the characteristics of an activity to be replicated in a resistance training environment.
- Contraction occurs through concentric and eccentric movement that cause muscles to work in pairs to perform an isolated or compound exercise.
- Free weight exercise develops inter and intra-muscular coordination which increases the ability to replicate a specific task or skill (ACSM 2002). Different muscle fibres exhibit individual characteristics, how these characteristics can be altered is discussed in the following section.
- Intra and inter muscular coordination can be evaluated using standardised tests such as a counter movement jump or vertical jump and the calculation of the rate of force and power development (RFD and RPD).
- The ability to generate force decreases as deviation from the resting muscle length increases (length-tension relationship).
- Power is a product of force and velocity, as the load is increased (force) the velocity decreases, therefore, the hyperbolic nature of the force-velocity curve must be considered when devising training programs to target power production.

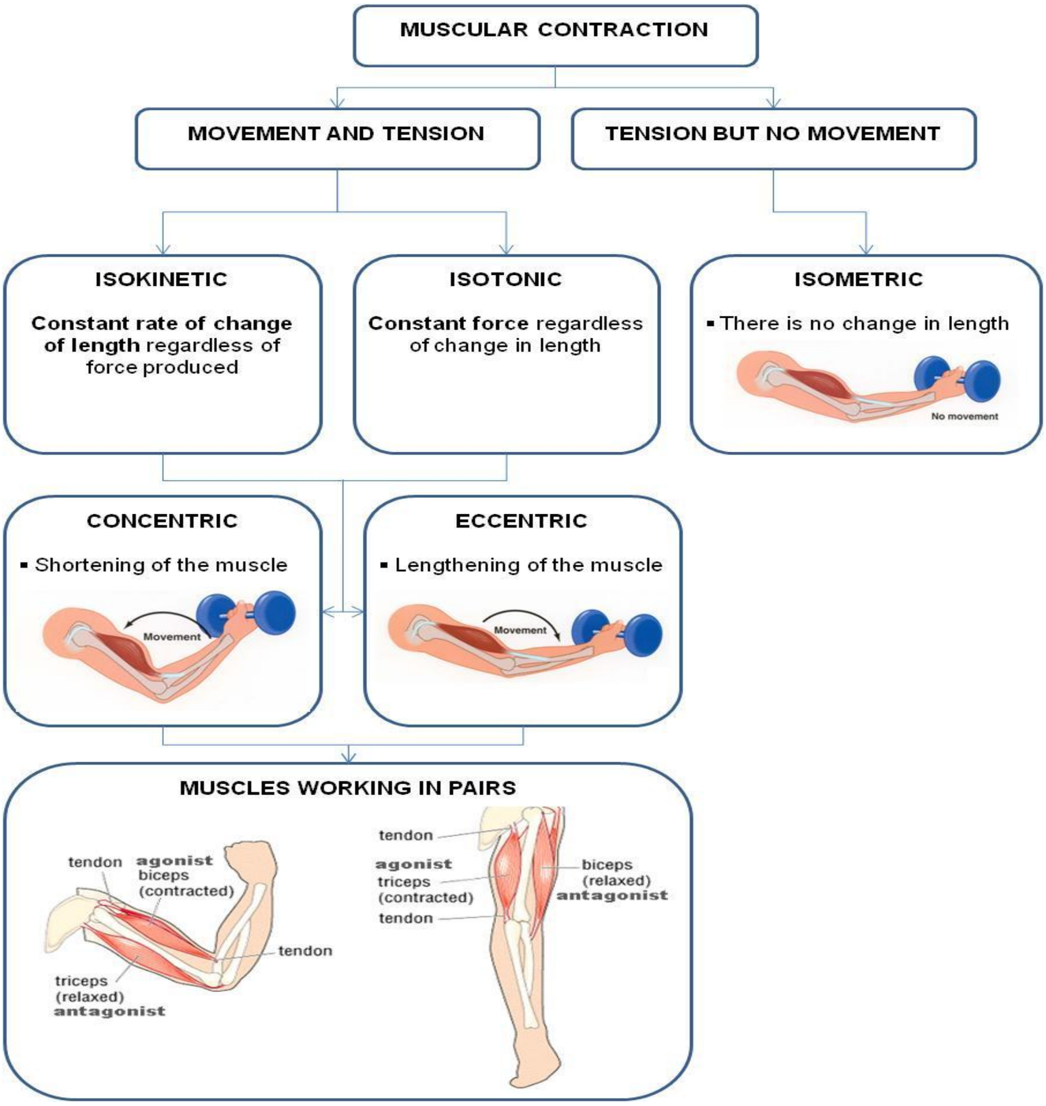


Figure 3.5 The different types of muscular contraction

3.3 The effects of resistance training

Resistance training can cause numerous adaptations both long and short term, all of which lead to an increased ability to generate force. The ability to produce more force may be the result of increased muscle cross sectional area (Alway 1999, McCall 1996 and Staron 1994), changes in the fibre composition (Kawakami 1993), enhanced neural function (Leong 1999 and Sale 1992), increased levels of metabolites (Rooney 1994 and Sforzo 1996), or a combination of these adaptations. These adaptations can influence the number and size of muscle fibres, the fibre type characteristics, heart rate, hormonal balance, the Central Nervous System response, body composition and fatigue resistance.

3.3.1 Hypertrophy adaptation

Research has shown resistance training induces muscular hypertrophy (Jackson 1990, McCall 1996 and Staron 1994) which is caused by an accumulation of proteins and can occur after just one session of vigorous training and increase the size of the muscle (Phillips 1997 and Phillips 2000). Short term increase in muscular size is referred to as "transient hypertrophy" and is caused by fluid accumulation of blood plasma. Long term resistance training can result in chronic hypertrophy, where increase in cross sectional area of the muscle can range from 20-45% (Staron et al 1991) and requires more than 16 workouts to produce significant effects (Staron et al 1994).

The ability of hypertrophy to increase force production is reliant upon the length-tension relationship. The length-tension relationship relates to the characteristics of individual sarcomeres, it is stipulated that the force produced in a sarcomere is directly related to the length of the muscle fibre at that instant (Smith 2007). Sarcomeres are arranged in parallel to the muscle, an increase in muscle size therefore increases the number of sarcomeres across the body of the muscle. Sarcomeres that lay in series do not affect one another collectively and will only exert the same amount of force as one sarcomere. Therefore, the overall force production of a muscle is proportional to its cross sectional area, the length of muscle does not influence force production (Jones and Round 1990). Consequently, functional hypertrophy can increase the number of sarcomeres available to increase force production and overall muscular strength.

However, not all hypertrophy enhances force production, hypertrophy can either be functional or non-functional as illustrated in Figure 3.6. Non-functional hypertrophy causes an increase in the non-contractile elements of a muscle fibre, predominantly occurring as a result of bodybuilding training (Thibaudeau 2007). This type of hypertrophy can lead to an increase in body weight, whilst excessive muscle hypertrophy can constrict the vascular system, which may decrease the ability to transport oxygen and nutrients to the muscle.

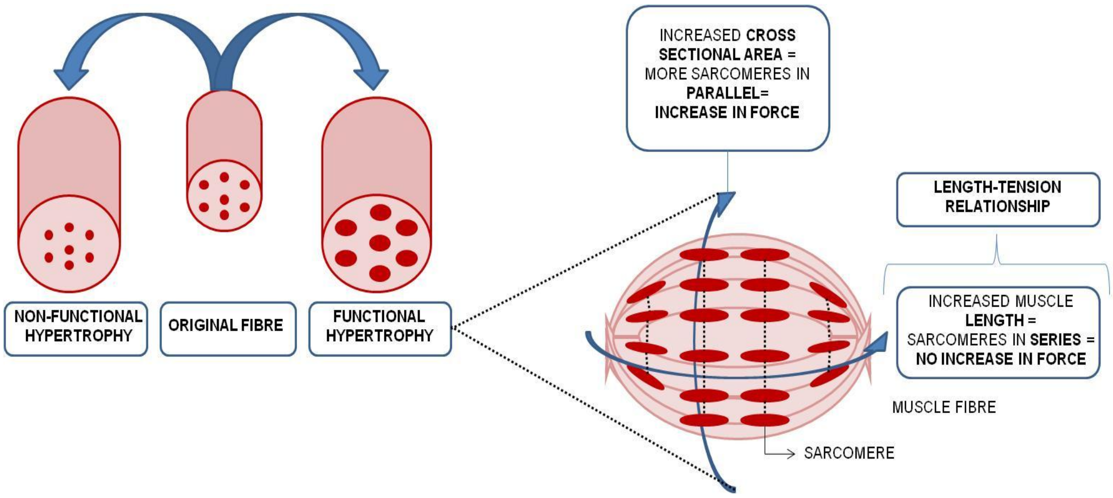


Figure 3.6 The difference between functional and non functional hypertrophy and ability to increase the number of sarcomeres in parallel.

3.3.2 Strength adaptation

Strength is the ability to produce force, this can be isometric or dynamic (Siff 1988 and Stone et al 2002). Force is a vector and therefore requires magnitude and direction, the force production is determined by the time period of muscle activation, the type of contraction, the rate of muscle activation and degree of muscle activation. Strength is often expressed by Newton's 2^{nd} Law where the acceleration of a mass depends on the ability to generate force, which in turn results in velocity. Consequently, weightlifting performance is highly dependent upon velocity and therefore reliant upon force production.

It is suggested that long-term changes in strength are attributed to hypertrophy of the muscle fibres or muscle group (Sale 1988). Variation in strength gains can range from 7% to 45% (Kraemer 1994) and elicit velocity specific characteristics, i.e increase in strength is specific to the training speed (Behm and Sale 1993). For example, slow speed training will result in greater gains at slow movement speeds, whilst high speed training will result in gains during fast movements. The importance of training speed is further enhanced by the force–velocity relationship. The force velocity relationship has been well researched and is commonly referred to as the "Hill curve" relationship (Hill 1983). This relationship demonstrates a decrease in force as the velocity of muscle shortening increases to a point at which no force can be exerted. There is an optimal level at which the lengthening velocity produces maximum force, this is often equal to or greater than the cross bridge cycle rate (Smith 2007).

3.3.3 Power adaptation

Power production is defined as the product of force and velocity or work rate (Siff 1988, Stone et al 2002 and Stone and Bryant 1987). Hence the measurement of strength and power are closely related (Rahmani et al 2001). The ability to produce force at speed is believed to be one the most important factors in most sports, particularly weightlifting (Stone et al 2006). The power-velocity relationship contrasts with the force-velocity relationship since as velocity increases, power output increases (Vandewalle 1987). However, increasing velocity is still restricted by the force-velocity relationship (Rahmani 2001), therefore increasing the muscular ability to generate force and designing training programs that alter training velocity can benefit the ability to increase power output.

3.3.4 Fibre type adaptation

Fibre type classification also affects the extent of hypertrophy related adaptation. Knowing an individual's ratio of muscle fibres can improve the specificity of the training program. For example, individuals who are slow-twitch dominant will benefit from higher volumes of training, whilst fast-twitch dominant athletes will progress further on a lower volume, higher intensity and acceleration training program (Thibaudeau 2007).
Muscle fibres are categorised as either (Scott, Stevens and Binder-McLeod 2001):

(1) Type I : slow twitch fibres which are recruited for aerobic activity, have a high resistance to fatigue but produce little power.
(2) Type IIa : Moderate-fast twitch fibres with medium fatigue resistance, recruited for long term anaerobic activity.
(3) Type IIx : Fast twitch fibres with medium to low fatigue resistance, recruited for short term anaerobic activity.
(4) Type IIb : Very fast twitch fibres with low fatigue resistance, recruited for short term anaerobic, high power activity.

Type I fibres (slow twitch) are red in colour due to the presence of myoglobin (oxygen binding protein) whilst Type II fibres (fast twitch) are white in colour due to the absence of myoglobin (Scott 2001). It is stipulated that fast twitch fibres exhibit greater potential to increase in size (Hather et al 1991). Overall, hypertrophy related muscle fibre adaptations are caused by subcellular changes within the muscle which include an increase in: (i) number and size of thicker actin and myosin protein filaments, (ii) the number of myofibrils that contain the actin and myosin filaments and (iii) the volume of sarcoplasm (the fluid in the muscle cell). Finally, hypertrophy occurs in the surrounding connective tissue of the muscle fibres (Wilmore & Costill 1994) and can result in functional and non-functional hypertrophy. Whether a person is Type I, IIa or IIb dominant is genetically determined, however, training adaptations can alter the characteristics of the muscle fibres (Nieman 2003). It is the capability to alter the characteristics of muscle fibres that provides one of the main advantages of resistance training.

3.3.5 Central Nervous System adaptation

Voluntary muscle contraction is primarily controlled by the nervous system. When a weak signal is sent to a particular muscle, the smaller motor units are stimulated first. As the signal increases, larger motor units can be recruited, these larger motor units can have up to 50 times the contractile strength than the smaller units. The strength of the signal also depends on the action potential sent from the Central Nervous System (CNS). The efficacy of the nervous system influences force production by modulating motor unit activation, synchronization and rate of contraction. Regular training can improve the CNS signal patterns and increase the recruitment of muscle fibres as motor control becomes more autonomous. Consequently, both CNS adaptation and functional hypertrophy is required to improve the capability to produce force and resultant muscular strength. It is suggested that short term changes in strength are more associated with neural adaptations (Moritani & deVries 1979).

Motor unit recruitment is central to the early gains in strength (2 to 8 weeks). The recruitment of additional motor units which are able to produce a synchronised response (Wilmore & Costill, 1994), the increased activation of synergistic muscles, and the inhibition of neural protective mechanisms (Kraemer 1994), all contribute to improved muscular ability to generate force. The CNS response also dictates the speed of contraction which influences the power output.

3.3.6 Fatigue resistance adaptation

Fatigue resistance is defined as "a reversible decrease in contractile strength that occurs after long lasting or repeated muscle activity" (Edman 1992). Muscular fatigue is caused by a build up of waste products when sufficient oxygen is not available. A build of lactic acid affects the cross bridge process within the muscle in three ways (Edman 1992):

1. By decreasing the number of interacting cross bridges,
2. Reducing the force output of the cross bridges,
3. Reducing the cross bridge cycle rate.

The adaptation of fibre type classification can influence the fatigue resistance. During prolonged resistance training periods, Type IIb fibres can develop Type IIa characteristics, making them less prone to fatigue (Staron et al 1994). Alternatively, extended endurance exercise can result in the adaptation of Type II fibres to Type I (Billeter and Hoppeler 1992). A list of other additional adaptations that can occur as a result of resistance training is presented in Table 3.3.

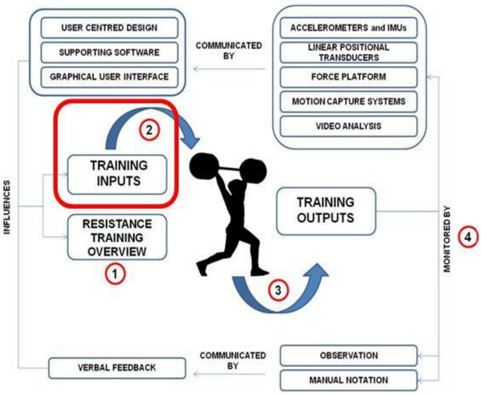
Adaptation	Research
Heartrate	Reduction in heartrate (Stone et al 1991) Reduction from 0% to 11% dependent on the training intensity.
Blood pressure	Dynamic resistance training with moderate resistance and high reps are associated with a reduction in blood pressure (Harris and Holly 1987). No change in blood pressure observed (Blumenthal et al 1991). More research required, views are varied.
Heart size	Increase in left ventricular wall thickness (Stone at el 1991),effect upon cardiac output and stroke volume is not understood.
Blood composition	Favourable changes in blood lipids and lipoproteins (Kokkinos and Hurley 1990). However, it is identified that more research is required due to the likely day to day fluctuation.
Glucose metabolism	Improvements in glucose metabolism with strength training, independent of alterations in aerobic capacity or percent body fat, have been shown (Hurley et al 1988), (Smutok et al 1993).
Body composition	Body composition is affected and controlled by resistance training programs using the larger muscle groups and greater total volume (Stone et al 1991). Energy expenditure following the higher total volume workouts appears to be elevated, compared to other forms of exercise, this further contributes to weight loss objectives.

Table 3.3 Other adaptations to resistance training

3.3.7 Training adaptation summary

- There are many benefits to resistance training both health and performance oriented, all of which stem from the ability to produce force.
- Increased force production is reliant upon functional hypertrophy, the cross sectional area of the muscle is increased and muscle fibre growth is accommodated.
- Increased muscular strength and force production also impacts the ability to generate power
- Adaptation of muscle fibre type and pulmonary system can increase fatigue resistance.
- Physiological and neural adaptation of the muscle can be achieved by resistance training, the type of adaptation is dependent on the type of training undertaken, which is ultimately by the identified training goals.
- The four main training goals that can be achieved through resistance training; endurance, hypertrophy, strength and power.
- Targeting different forms of adaptation (endurance, hypertrophy, strength and power) is dependent upon controlling training inputs and acute variables.

3.4 Section 2: Training inputs



TARGET RESEARCH QUESTIONS:

- *What are training inputs?*
- *How can training inputs be manipulated to train for endurance, hypertrophy, strength and power?*
- *How are training inputs monitored?*

Designing a training program is reliant upon manipulation of training inputs and observation of the training outputs. Each input can be altered to train for either endurance, hypertrophy, strength or power. Effective training programs therefore require regular performance analysis of the training outputs in order to identify whether the desired adaptation is being targeted. According to the ACSM (2002), in order to achieve progression and target endurance, strength, hypertrophy or power, 7 training inputs can be adjusted (identified in Figure 3.7). These inputs influence which training outputs are most affected and whether the effect is positive or negative. The training outputs include kinetic and kinematic variables of the bar and body. An overview of training inputs and outputs is presented in Figure 3.7.

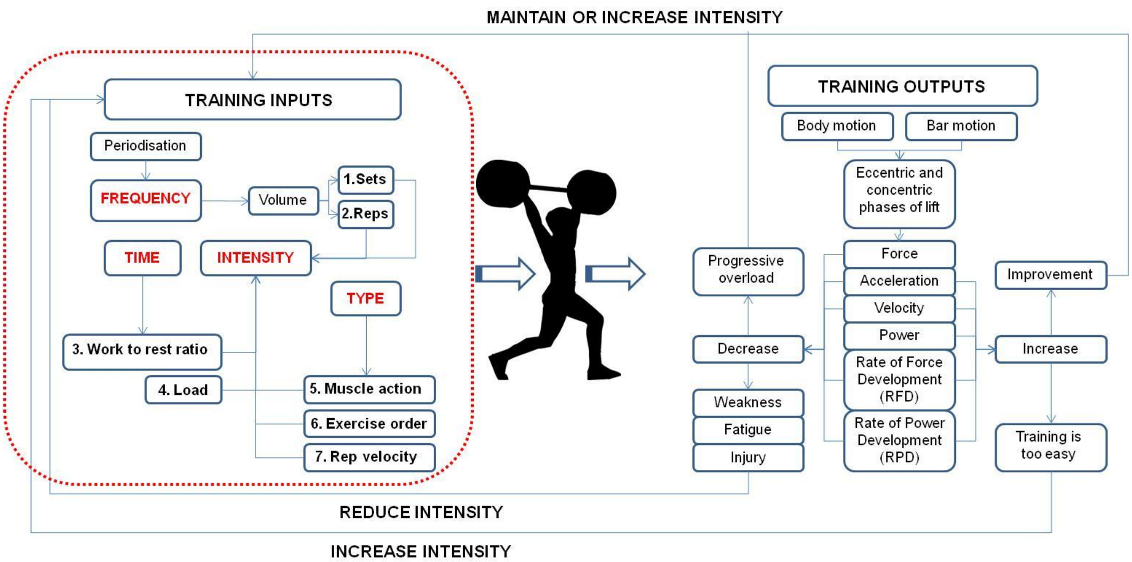


Figure 3.7 An overview of training inputs and outputs

Effective training program design is reliant on targeting individual needs by controlling the training inputs. The most influential variables are adapted using the "FITT principle" (ACSM 2010). The components of the FITT principle are also identified in Figure 3.8. This principle refers to the variables of frequency, intensity, time and type of activity (FITT) which form the basic structure of well planned training programs. The application of these principles to resistance training is detailed further in Table 3.4.

Principle	Explanation
Frequency	The number of resistance training sessions per week and relates to the volume of work done.
Intensity	Determined by the number of sets and reps, volume of work and rest periods.
Time	The rest to work ratio
Type	The chosen training system, muscle action and exercise order

Table 3.4 The FITT principle applied to resistance training

The ability to alter these inputs effectively and target specific goals requires application of the strength-endurance continuum (Nieman 2003). The strength-endurance continuum is used as the basis for most training programmes, it provides basic guidance on the resistance, repetitions, energy systems and fibre type to determine whether the output is strength or endurance based. However, these are broad guidelines and do not distinguish between the four training zones of endurance, hypertrophy, strength and power. Consequently, the strength-endurance continuum has been further developed to determine optimum training conditions that target the four training zones.

This revised continuum specifies the intensity through manipulation of load using the repetitions (one weight training or calisthenic movement (reps)), sets (a certain number of weight training or calisthenic repetitions), percentage of a one repetition max ((1RM) a percentage of the maximum number of repetitions that one can lift at a certain weight) and rest time (time period between sets) (Nieman 2003). The relationship between the volume of work (sets and reps), rest time and load is presented in Figure 3.8 (ACSM 2010).

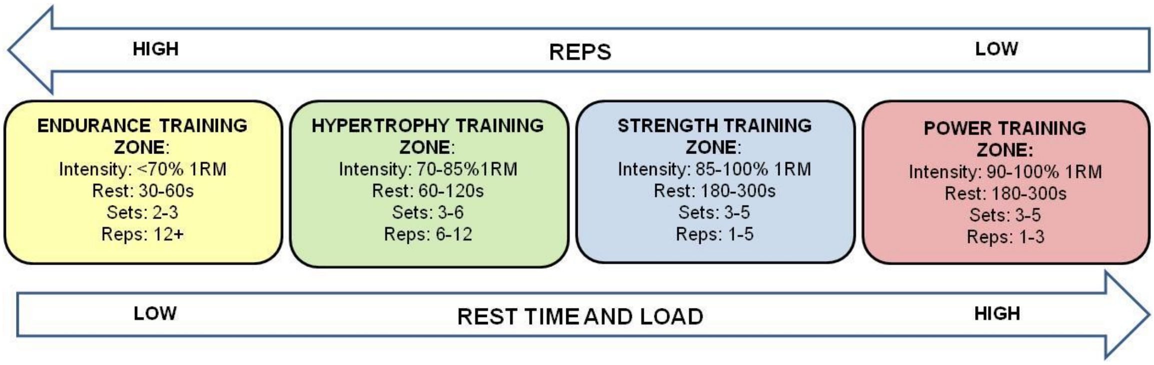


Figure 3.8 The acute variables required to target the four training systems; endurance, hypertrophy, strength and power

The main training inputs are listed in the bullet points below. How each can be adjusted to target endurance, strength, hypertrophy or power is discussed in further detail in Sections 3.4.1-3.4.3.

- Frequency
- Volume
- Load
- Rest to work ratio
- Muscle action
- Exercise order
- Rep velocity (slow (0.15 +/- 0.03 m.s), moderate (0.32 +/- 0.07 m.s) and high (0.52 +/- 0.12 m.s).

3.4.1 Training for endurance

Research has shown that muscular endurance can be improved by resistance training (Anderson and Kearney 1982, Huczel and Clarke 1992, Marcine et al 1991, Marx et al 2001 and McGee et al 1992). It is believed that moderate to low resistance with high repetitions (15-20+) is the most effective form of endurance training (Housh et al 1992). However, moderate to heavy loading coupled with short rest periods can also increase high intensity muscular endurance (Anderson and Kearney 1982 and McGee et al 1992). Rest intervals significantly affect endurance training. Research has shown that high volume- short rest periods can increase fatigue resistance (Kraemer et al 1987). Training is most effective with large muscle groups with both isolated and compound exercises recommended for varied user levels (ACSM 2002). The exercise order is less important when training for hypertrophy, strength or power as fatigue is a necessary component of endurance training (ACSM 2002). Studies have also shown than increased training velocity improves muscular endurance more than slow speed training (ACSM 2002). It is recommended by the ACSM that slow velocities should be used for 10-15 repetitions, whilst moderate to high velocity is more suitable for higher repetitions (15-20+). Studies have also indicated that a frequency of 2-3 sessions per week is effective for both novice and intermediate men and women (Hickson et al 1994 and Staron et al 1994).

3.4.2 Training for Hypertrophy

Moderate to heavy loads have been found to stimulate hypertrophy, whilst programs are typically high in volume (Kraemer 1992). It is recommended that training with loads between 70-85%1RM, repetitions between 6-12, sets between 3-6 and rest periods between 60-120 seconds are most effective. Both isolated and compound movements are appropriate for hypertrophy training. The recommended order in which the exercises should be performed (exercise order) is such that large muscle groups (e.g the quadriceps, hamstrings) are exercised first, whilst multi-joint exercises should be performed before single joint exercises. Finally, repetition velocity is a less documented variable regarding hypertrophy, however, it has been suggested that slow to moderate velocities should be used by novice and intermediate individuals, whilst advanced individuals may require higher velocities (ACSM 2010).

3.4.3 Training for power and strength

Dynamic muscular strength improvements are greatest when eccentric actions are included in the reputation movement (Dudley et al 1991). Some advanced programs utilise isometric training to increase muscular strength (Keogh et al 1999). Training with loads between 1-6 RM is most conducive to gains in maximal dynamic strength. It is recommended that to increase strength both free weights and machines should be used at the novice and intermediate level, advanced performers should focus on free weight training alone. Rest periods between 2-3 minutes are required, whilst training at a range of velocities is recommended for advanced training. Within strength training, it is recommended that the order in which the exercises are performed should match that of hypertrophy training (large muscle groups are exercised first, whilst multi-joint exercises should be performed before single joint exercises). Power training utilises very similar principles to strength training, but focus is upon maximising repetition velocity, higher loads may be used but rest periods remain the same as those for strength training. An overview of the recommended guidelines to train for endurance, hypertrophy, strength or power is presented in Table 3.5. It is clear from the overview that there are many inputs to monitor to ensure the training program meets the goal of the individual. Changing the sets, reps, load and rest time can have a significant effect on the training effect and resultant adaptation. Monitoring these inputs and understanding their effect is therefore an important part of training program success.

Table 3.5 Overview of the acute variables to training for endurance, hypertrophy, strength and power (ACSM 2010 and Discovery Learning 2010).

Training	Frequency	Volume	Load	Rest to work ratio	Type	Exercise order	Rep velocity
Endurance	2-3 sessions per week	Sets: 2-3 Reps: 12+	Light to moderate <70% 1RM	1-2mins for high reps (15-20), 1 min for moderate reps (10-15)	Large muscle groups, combine isolated and compound exercises	Not important as fatigue is necessary	Moderate reps= slow velocity High reps: high velocity
Hypertrophy	2-3 sessions per week (depends on number of muscles trained per session).	Set: 3-6 Reps: 6-12	70-85% 1RM	60-120 seconds	Both isolated and compound	Compound before isolated and multi joint before single joint.	Novice and intermediate= slow, advanced= high
Strength	Novice = 2-3 Advanced= 4-5 days per week	Sets: 3-5 Reps: 1-5	85-100% 1RM	180-300 seconds	Both isolated and compound	Compound before isolated and multi joint before single joint.	Novice and intermediate= slow, advanced= range from slow to high
Power	Novice = 2-3 Advanced= 4-5 days per week	Set: 3-6 Reps: 1-3	90-100% 1RM	180-300 seconds	Predominantly multi joint compound exercise for novice, intermediate and advanced.	Compound before isolated and multi joint before single joint.	Novice and intermediate= medium, advanced= high

3.4.5 Current methods to monitor training inputs

Free weight training in the gym environment mainly relies upon manual notation of sets, repetitions, load and rest time. Most individuals from novice to advanced levels who adhere to a structured program follow a session that is manually noted in a notebook or on paper. This program may have been obtained using online or other media sources, some may be following a program designed by a personal trainer, whilst more advanced individuals may have programs designed by their coach. Despite the training inputs being a fundamental part of training success, individuals often attend the gym without any structured program. They may either follow a structure they learned previously or do not follow any structure at all. In both cases, progressive overload is difficult to achieve (ACSM 2002).

The current gym environment is dominated by cardiovascular machines that enable the user to input relevant training inputs via an interactive interface (Rosandich 2000 and Chang 2007). The user is able to personalise their workout by selecting specific training programs, inputting their weight and selecting the data that they would like to see during their workout. Some devices also allow the user to insert a USB memory stick to save their workout profile and resultant performance data (Life Fitness© 2012). Not only does this reduce the set up time, it further personalises the user experience. Overall, regardless of individual experience and desire to follow a structured program, in the resistance training domain, all quantitative training inputs are currently documented manually which result in any number of the problems listed in Table 3.6.

Variable	Problem
Load	• Reliant on manual notation, subject to human error. • Recalling what loads were used in previous sessions is difficult, especially when multiple exercises require various 1RM values (Chang 2007).
Volume	• Reliant on manual notation, subject to human error. • A novice may use unsuitable volume and load that may cause or injury or prevent adaption. • There is no definitive record for coaches to identify whether a session was completed without direct observation.
Rest	• Monitoring the time accurately is dependent on a training partner/coach, or having a timer that can be set to work and rest periods.
Progression	• Keeping records and viewing progression or lack of progression over an extended period of time is difficult. • Reliant upon manual notation.
Rep velocity	• Has to be gauged by the individual or coach, quantitative data cannot be obtained without post analysis. • Not accessible to recreational users.

Table 3.6 The current limitations when monitoring training inputs in the resistance training domain.

3.4.6 Summary of training inputs

The relationship between the training systems, acute variables, specificity of the program and overall influence of periodisation is illustrated in Figure 3.9. Overall the key points regarding resistance training inputs are as follows:

- Resistance training is dependent upon the ability to generate force.
- Free weights exercises have been shown to provide more training benefits than machine based exercises.
- The extent and type of adaptation is dependent on the muscle actions, intensity, volume, exercise selection, exercise order, rest periods and frequency (Tan 1999).
- The FITT principle involves manipulation of the load, sets, reps and rest time to target four training systems: endurance, hypertrophy, strength and power.
- Progressive overload is required to improve performance (ACSM 2002).
- The structure of the overall program is based upon the principle of periodisation.
- Effectiveness of the training inputs is quantified by analysis of the training outputs.
- Monitoring training inputs is heavily reliant upon manual notation at the advanced, intermediate and novice level.
- The ability to monitor training inputs in the free weight domain is limited.

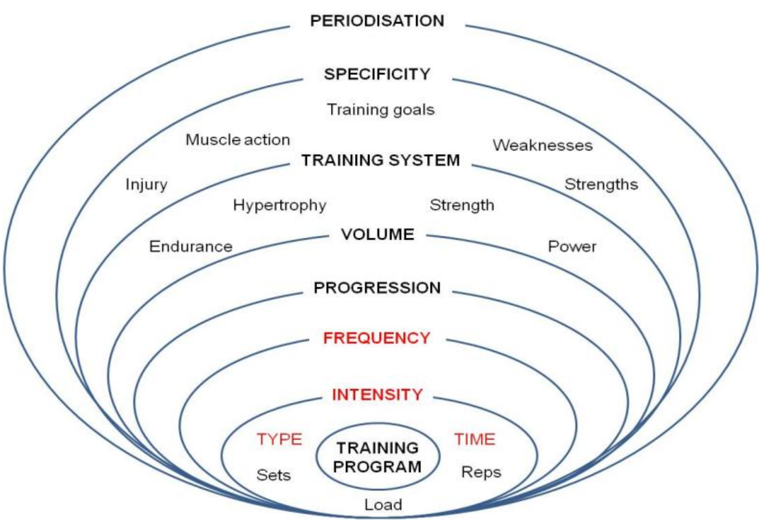
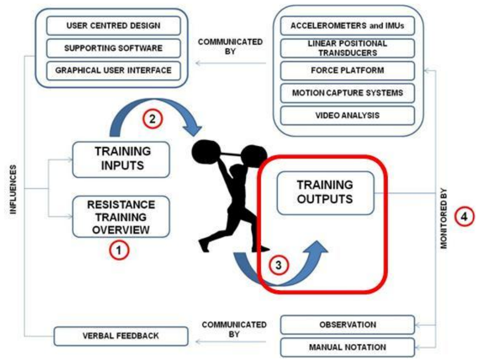


Figure 3.9 The relationship between the training inputs to create an effective training program



3.5 Section 3: Training outputs

TARGET RESEARCH QUESTIONS:

- *What are the training outputs monitored within the resistance training domain?*
- *Which training outputs have received most research focus?*

The success of a training program is determined by the training outputs and whether they match the set training goals of the individual. The training outputs associated with resistance training performance are identified in Figure 3.10. Monitoring performance from a novice to advanced level requires analysis of both bar and body motion to ensure that technique is considered (Stone et al 1998, Schilling et al 2002 and Winchester et al 2009). Some exercises may cause the body to move with the bar (such as the squat), however, other exercises, require the individual to move the bar independently of the body, resulting in kinetic and kinematic data relating to both the bar and body (such as the snatch). Therefore, a number of research programmes focusing on the kinematics of the bar and corresponding bar position are being undertaken to characterise successful lifts (Winchester 2009 et al, Bartoneitz et al 1996 and Campos et al 2006).

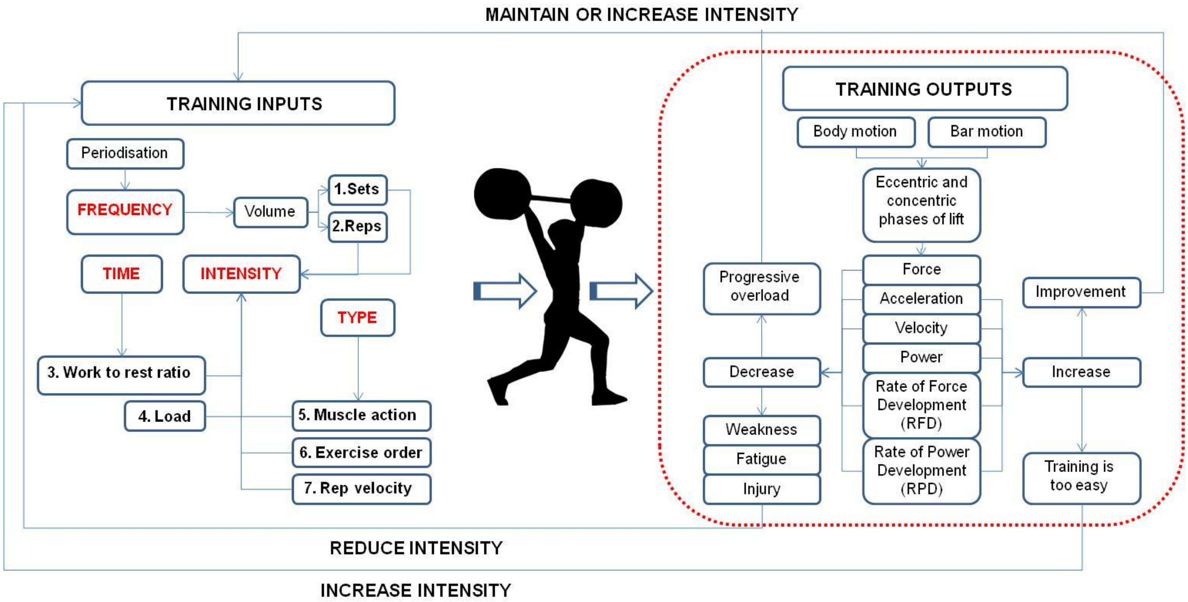


Figure 3.10 Training outputs

Determining the characteristics of motion and forces causing motion is concerned with kinetics and kinematics. Kinetic information is paramount for the analysis and guidance of athletic sports (Gao et al 2008) and is concerned with what causes a body to move (Zatsiorsky 2002). Kinematics is a branch of dynamics that deals with aspects of motion apart from considerations of mass and force, this may involve position, velocity, linear and rotational acceleration (Bartlett 2007). Increased demand across sporting domains for detailed analysis of technique and it's effect on performance, has led to research focusing on human movement and methods of functional analysis (Knutzen 1998). However, some kinetic and kinematic data is more important to some sports than others. Understanding which have the most effect within the resistance training domain is discussed in the following section. Evaluation of current research within the resistance training domain has been conducted to determine which variables have been researched heavily using a variety of technologies. The variables that have received most research focus include the bar trajectory, force, acceleration, velocity, power and fatigue.

3.5.1 Bar trajectory

Of the kinematic variables studied by coaches and sports scientists, bar path has been highly documented. It is suggested that it is a significant measure of technique (Barry 1993) whilst patterns of bar movement can identify the most efficient path (Hiskia 1997, Schilling 2002, Stone 1998 and Winchester 2005), particularly at high performance levels where complex lifts are performed in training and require detailed analysis. It has been suggested that there is a relationship between establishment of certain bar path kinematics and the level of success (Sewell 1988). At the advanced level, four important elements have been identified as important factors in determining the success of weightlifting performance (Winchester 2009):

1) Initial rearward movement of the bar during the first pull.
2) A catch position no more than 20cm behind the most forward bar position.
3) Amount of looping (i.e deviation of the bar trajectory from the midline of the body) which should be less than the net rearward horizontal displacement.
4) Relationship between weight lifted and velocity in which the time interval from the start of the lift to peak velocity increases as weight increases, whilst peak velocity decreases (Garhammer 2001).

The relationship between optimal bar path kinematics and power and force production is an area of growing research. Previous kinetic analysis has highlighted the need for maximal force production during the second pull of a power snatch (Souza 2002). Whilst, improvements in both power and force production were documented for the power clean following bar kinematic correction (Winchester 2005), there is an established link between bar kinematics and kinetic variables such as the Ground Reaction Force (GRF) and resultant power output (Stone 1998). According to Baumann (1988), the extent of the horizontal movement determines the correction (i.e the additional force and power required to bring the bar back towards the midline of the body) required to complete the lift.

3.5.2 Force

As the ability of the neuromuscular system to generate force is necessary for all types of movement (ACSM 2002), the ability to generate force is the main performance characteristic of resistance training. Exerting force is associated with muscular strength as the ability to lift a heavy load is perceived as being "strong". Force is the product of mass and acceleration and understanding the relationship between all three variables is important as it maximises the capacity to produce force in a session, prevents selection of redundant exercises and ensures that rate of progression is safe (Thibideau 2007).

The rate of force development (RFD) is also a key characteristic of performance, it is defined as the rate of rise of contractile force at the beginning of a muscle action and is related to the acceleration capability of the performer (Aagaard et al, 2002). This is due to the tendency for critical aspects in strength and power sports to occur in very short time frames (< 250milliseconds (Schmidtbleicher 1992)). Consequently, if an athlete can produce greater force within this time period, higher velocities and accelerations can be achieved. Previous research suggests that stronger athletes also have a higher RFD (Haff et al 1997).

3.5.3 Acceleration and velocity

Focus upon the acceleration experienced during resistance training is less documented. Although acceleration is often calculated to obtain other results such as velocity and power, few studies have focused on the observation of acceleration alone (Sato 2009).

Velocity has been more documented as a fundamental characteristic of successful lifting performance. The velocity of muscular contraction used to perform dynamic muscle actions affects neural, hypertrophic and metabolic responses to exercise (ACSM 2002) and (Housh et al 1992). It is recommended by the ACSM that untrained individuals should train at slow and moderate velocities, intermediate individuals should train at moderate velocities, whilst for advanced training, a continuum of velocities should be used to maximise strength gains. As velocity is a component of power, increasing velocity can increase power output, however, a balance between force and velocity is required due to the force-velocity relationship (Rahmani et al 2001).

3.5.4 Power

Power (P) is described as work done per unit of time, or more commonly in relation to sport, a product of force (F) and velocity (V) (P = F x V). More power is produced when the same amount of work is done in a shorter period of time (ACSM 2002). As both high force and velocities are required, untrained individuals cannot begin training at this level without the risk of injury. Power is also influenced by rate of force development (RFD), strength at high and low velocities, stretch shortening performance and coordination of the movement (Schmidtbleicher 1992, Young 1998 and ACSM 2002). The rate of power development (RPD) has also been a focus of research, in which the peak power and time to peak power are used to calculate the rate of power development (Koshida 2008). Power output has been frequently used as an indicator of successful performance through the use of force platforms and positional transducers. Strength and conditioning specialists often measure power output to evaluate an athlete’s strength at speed (Newton and Dugan 2002). Although many studies have measured power output during a squat jump (Baker 2001, Baker 1999, Chui et al 2003, Dugan et al 2004, McBride et al 1999, McBride et al 2002, Newton et al 2009 and Wilson et al 1993), few have focused upon free weight training alone (Haff et al 1997, Haff 2003, Kawamori and Haff 2004, Moore et al 2003 and Winchester 2005).

3.5.5 Fatigue

Fatigue can be described as an exercise induced reduction in the maximal force capacity of muscle (Hunter 2004). Research has documented decreases in force and velocity (Westerblad 1998) and power (Halson 2002) as level of fatigue increases (10-20%

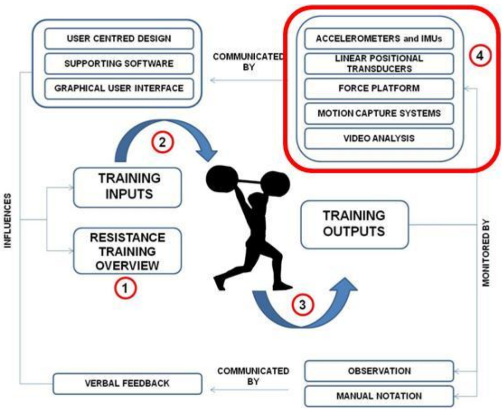
reduction of maximum force and power). An individual may therefore, exhibit numerous signs of fatigue, e.g a reduction in force which may impact RFD, velocity, power or RPD. As such, the ability to monitor these parameters is of great interest, particularly at the competitive levels where improved performance is desired. From a health perspective, the ability to monitor these parameters would highlight the need to strengthen weaker muscles and improve motor control. It is believed that motor control and concentration can be affected by fatigue (Halson 2002) which could lead to reduction in reaction time, balance, coordination and the ability to stabilize the working muscles.

An overview of the most relevant research studies conducted in the resistance training domain is presented in Table 3.7. The first author, performance variable(s) and exercise of interest are listed to identify which variables are most commonly researched. A total score is also calculated based upon the number of studies investigating each variable. The studies are listed in chronological order so that any trends in the research directions can be identified. The results indicate that the most commonly researched variable is peak force. Both peak velocity and peak power are the second most reported variables, whilst bar trajectory is the third most common. Although the information presented in Table 3.7 is not an exhaustive list, it is clear that the ability to monitor peak force, peak velocity and peak power is of great interest to both sports scientists and coaches alike. Numerous forms of technology have been used to collect the identified kinetic and kinematic data including video, force platforms, linear positional transducers (LPT's) and sensor technology. How training outputs are monitored using this technology and the limitations of each, are discussed in the following section.

First author	PF	AF	RFD	PV	AV	PP	AP	RPD	A	BT	Exercise
Bartonletz (1996)				●						●	Snatch
Gourgoulis (2000)				●			●		●	●	Snatch
Rahmani (2001)	●			●		●					Squat
Souza (2002)	●	●									Power Clean
Haff (2003)				●		●			●	●	Clean pull
Sleivert (2004)						●	●				Squat Jump
Manne (2006)								●		●	Bench press
Hori (2006)	●			●		●					Squat Jump
Chang (2007)									●		Varied
Bruenger (2007)										●	Power Snatch
Jenson (2008)	●		●								Squat Jump
Nejadien (2008)				●						●	Snatch
Rambaud (2008)	●			●		●					Bench Press
Koshida (2008)	●					●		●			Bench press
Winchester (2009)	●					●				●	Power Snatch
Patterson (2009)	●						●				Squat Jump
Sato (2009a and b)									●		Snatch & Clean
Frost (2010)	●			●						●	Bench press
Hanson (2010)	●		●								Squat Jump
Dayne (2011)	●			●		●					Squat Jump
Lake (2011)	●				●		●		●		Squat
Crewther (2011)	●					●					Squat Jump
TOTAL	**13**	**1**	**2**	**9**	**1**	**9**	**4**	**2**	**5**	**8**	

Table 3.7 Summary of research within the resistance training domain to identify the most influential performance variable,

**PF: Peak Force, AF: Average Force, RFD: Rate of Force Development, PV: Peak Velocity, AV: Average Velocity, PP: Peak Power, AP: Average Power, RPD: Rate of Power Development, A: Acceleration, BT: Bar Trajectory.



3.6 Section 4: Current monitoring technology

TARGET RESEARCH QUESTIONS:

- *What forms of technology are currently used to monitor performance in the resistance training domain?*
- *What are the limitations and resultant gaps in current research methods and technology development?*

Many tools have been developed to assist resistance performance analysis, including video analysis, electromyography, force platform analysis, simple timed measures, questionnaire tools, validated functional tests and human expert observation (Mathie et al 2004). An evaluation of the technologies that has been applied to the resistance training domain, the derived performance variables and methods of calculation is documented in this section. Research that has been conducted using each form of technology and the limitations of each is also discussed.

3.6.1 Video

Video technology is a commonly used tool that provides feedback through post session analysis of the video stream. The portability, ease of interpretation, low cost and accessibility of video technology ensures that it is the preferred tool of coaches and athletes (Leibermann 2002). More advanced systems have integrated supporting software that provides qualitative and quantitative data on body and bar movement through post analysis. Commercial analysis systems include: SportsCode (Sportstec© 2008), SiliconCoach Pro (Silicon Coach© 2010) and Quintic Biomechanics 9.03v17 (Quintic Consultancy Ltd© 1996). Some systems also provide a form of comparative feedback allowing an athlete’s performance to be compared to an ideal template (Leibermann et al 2002). Although the aim is to provide “user friendly” technology a major problem with a comparative system is how well a template can represent a large population range. This argument is supported by Knudson and Morrison (1997) who state that an individual's optimal performance is unlikely to be the same as that of another.

Video analysis is considered one of the most accessible forms of performance analysis; it is therefore often used alongside other monitoring methods to provide "gold standard" measurements. The ability to relate quantitative data to technique is heavily reliant on knowledge of the corresponding movement. Therefore, although video analysis is time consuming, it is a reliable method that can be used to validate other performance monitoring systems. An example of a digitised bench press trajectory using video analysis is presented in Figure 3.11.

Most research publications detail the calculation of performance variables using video displacement data, requiring double differentiation of displacement data to determine acceleration coupled with the system mass to calculate a measure of force output (see Figure 3.12), (Falvo 2005, Newton and Dugan 2002, Baker 2001, Cormie et al 2007, Baker et al 2001, Bourque and Sleivert 3003, Izquierdo 1999,2001,2002, Alemany et al 2005, Cronin and Henderson 2004, Rahmani et al 2001, Thomas et al 1996 and Weiss et al 2004, 2005). The direct acquisition of displacement data to derive other kinetic and kinematic variables can also provide a visual method of synchronisation with other monitoring devices, ensuring that video analysis is rarely used in isolation in research.

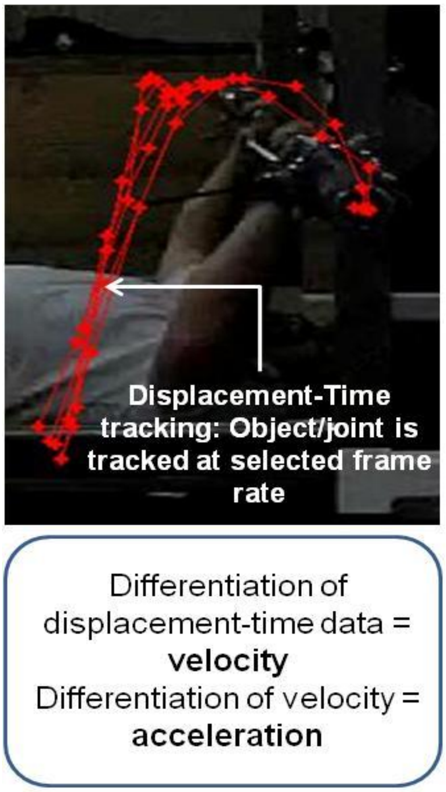


Figure 3.11 An example of the digitisation process.

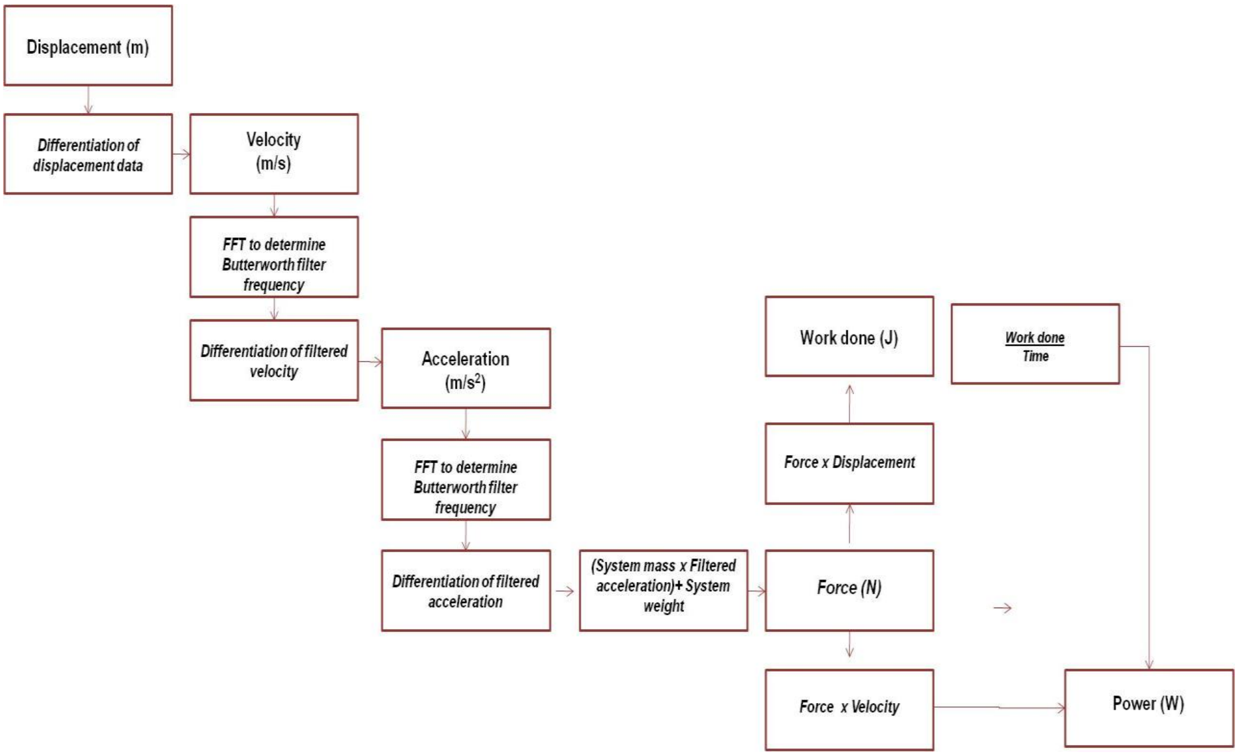


Figure 3.12 The calculation of kinematic data using video displacement data

3.6.2 Force Platforms

Force platforms have a wide range of applications in the health, engineering and sports domains (Leibermann 2002). A force platform is most commonly designed as a rectangular metal plate, with piezoelectric or strain gauge transducers attached at each corner to give an electrical output that is proportional to the force on the plate. The piezo-electric or strain gauge transducers measure the force exerted against it by the subject or object. According to Newton's third law of motion (every action has an equal and opposite reaction) this also measures the force exerted by the platform against the subject or object. The force exerted by the platform against the body is often referred to as the "Ground Reaction Force" (GRF) (Linthorne 2001).

Force platforms are commonly used to investigate the kinematics and dynamics of human motion. Supporting software is often used to derive acceleration, velocity and displacement data from the force-time curve through post session analysis. The acceleration-time curve is obtained by dividing the force-time curve by the subject's body mass, the velocity-time curve can then be obtained by numerically integrating acceleration-time curve using the trapezoid rule. Although more complex integration methods can be used, such as Simpson's rule, research suggests that accuracy is not significantly improved (Kibele 1998). The trapezoid rule is therefore a sufficient method for deriving kinematic data using force platform technology. Direct kinetic analysis using a force platform is also used to calculate power from the GRF. This relies upon determining the impulse-momentum relationship to determine velocity and resultant power. Typically this method has been applied to vertical jumps rather than loading and resultant power output (Haff et al 1997, Dugan et al 2004, McBride et al 1999, Delecluse et al 2005, French et al 2004, Iossifidou et al 2005, and Sands et al 2005). Power can be derived from the derived variables using one of two methods:

1. ***Power*** = $Force\ x\ Velocity$
2. ***Work done*** = *Force x Displacement* ⇨ ***Power*** = $\frac{Work\ done}{Time}$

The first method relies upon the GRF data and derived velocity-time data following integration of the acceleration-time data. The second method utilises the original GRF data and requires double integration of the acceleration-time data to calculate the displacement. The first method involves less data manipulation which reduces the risk of human error and integration error accumulation. The calculation process to derive acceleration, velocity and power from the GRF data is presented in Figure 3.13. The calculation of power has been separated into the double and single integration methods. The double integration method requires three extra steps and therefore may not be the most efficient method of power calculation.

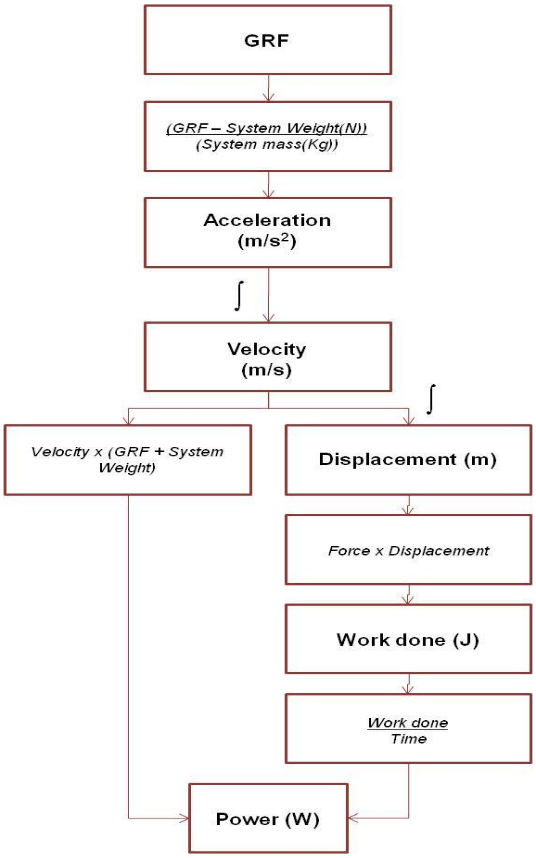


Figure 3.13 The calculation of kinematic data from force platform Ground Reaction Force (GRF) data.

Numerical integration of force-time curves also allows jump height data to be derived during post session analysis. The ability to integrate the force-time data to derive take off velocity and time in flight has resulted in multiple jump height calculation methods. Time in the Air (TIA) is a commonly used method in which the vertical displacement of the centre of mass (COM) is calculated using an equation of uniform acceleration (Beynnon and Johnson 1996). A jump is defined as "a vertical displacement achieved by a COM from take off to the vertex of the flight trajectory" (Moir 2008). This requires consideration of the time of flight only. However, using this method, it is assumed that the position of the COM is the same at the beginning before take-off and upon landing which may or may not be the case, leading to subsequent questioning of the validity of TIA calculation (Bosco et al 1983). Another method involves calculating the vertical velocity of the COM at take off by integrating the force trace and using an equation of uniform acceleration to determine the jump height (Moir 2008). This avoids the assumption that the COM is the same at takeoff and landing but does not account for the change in vertical displacement that will occur due to joint extension. It is suggested that the COM vertical displacement can be readily calculated using video based systems (Hatze et al 1998). Double integration of the vertical force data can be used to estimate the COM displacement achieved during a lift (Beynnon and Johnson 1996). Therefore the third method involves consideration of the take off velocity and COM position at take off (Aragon-Vargas 2000). The three calculations are illustrated in Figure 3.14.

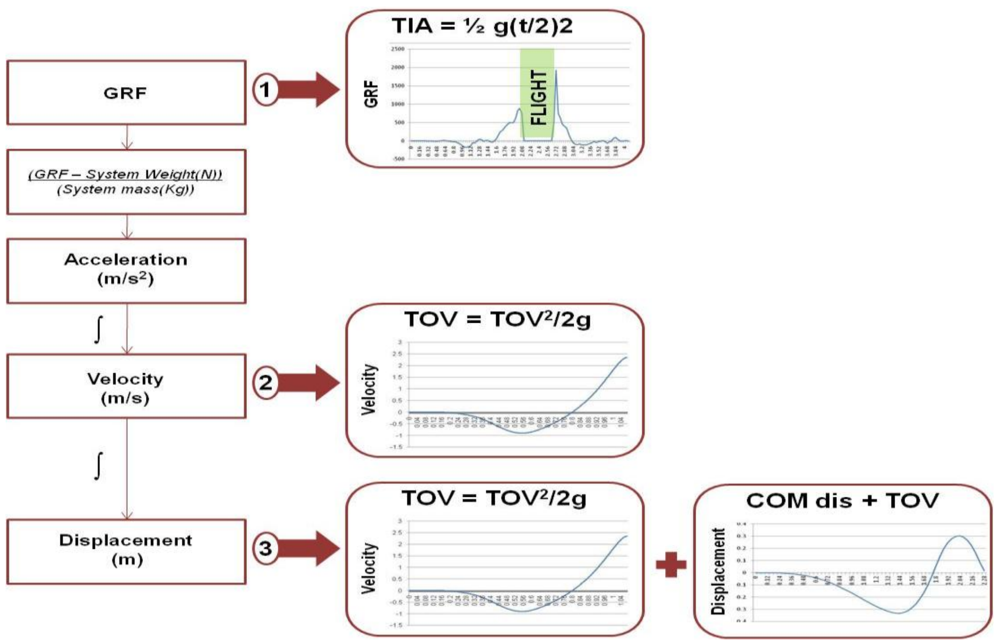


Figure 3.14 The three common calculation methods to calculate jump height, 1. Using time in the air, 2. Using take off velocity and 3. Using centre of mass displacement and take off velocity.

Jump analysis is a performance monitoring method well utilised across the sporting domain (Tidow 1990 and Young 1995). Readiness to perform is commonly investigated using a squat jump or vertical jump, the jump height reached is used as an indicator of the readiness to perform (Thibadeau 2007). The ability to monitor both dynamic jump and human motion using a force platform would provide an abundance of data to characterise performance in a gym environment. Force platforms may be classified according to whether they are single-pedestal (load cells), multi-pedestal and by the transducer type (strain gauge, piezoelectric sensors, capacitance gauge or piezo-resistive) (Griffiths 2006). Load cells are most suited to the monitoring of forces applied over a small area, for applications such as gait analysis in which forces migrate across the plate, multi-pedestal platforms are required. As the number of load cells increases, the cost of the force platform also increases due to increased accuracy. The computation of the ground reaction force (GRF) is represented by three vectors, force, centre of pressure and a free moment. The force is calculated using the x, y and z vector, however, the force platform cost can be reduced if only the horizontal component (z) is of interest as less load cells are required. Performance analysis involving movement across the plate both horizontally and vertically (such as gait analysis) would not be well represented using horizontal force alone. Therefore, the type of application and level of accuracy required influences the cost of a force platform.

The direct acquisition of kinetic data using a force platform is not always a cost effective solution (typical force platforms cost between £15-30k) and is often limited to lab based environments (Cronin 2004) and (Walsh 2006). In addition, a skilled user is required to post process and analyse the data, whilst real time feedback is not currently possible. Therefore, force platform use within a gym environment may be more suited to an elite gym environment rather than recreational. Consequently research focus has shifted towards the application and development of kinematic systems such as linear positional transducers and accelerometers to monitor resistance training performance (Crewther et al 2011).

3.6.3 Linear Positional Transducers (LPT's)

An LPT consists of a tethered cord which is attached to the end of the weight training bar to extract time-displacement data which can be used to calculate velocities and accelerations (Crewther 2011). Literature documents the calculation of performance variables through either displacement data using a single LPT requiring double differentiation of displacement data to determine acceleration coupled with the system mass to calculate force output (Falvo 2005, Newton and Dugan 2002, Baker 2001, Cormie et al 2007, Baker et al 2001, Bourque and Sleivert 3003, Izquierdo 1999,2001,2002, Alemany et al 2005, Cronin and Henderson 2004, Rahmani et al 2001, Thomas et al 1996 and Weiss et al 2004, 2005). These kinematic data can be used to estimate force and power when the mass of the load and subject are factored in (Cronin 2007b) and (Drinkwater 2007). Relative validity (correlation) statistics have been reported as r=0.86-1.00 using a single linear transducer (Crewther 2011). However, absolute validity (i.e agreement between the calculated mean values) has shown significant difference. Research has shown differences in power values using a single LPT (average jump squat power derived using single LPT analysis (3379.56 ± 505.8W) in comparison to force platform analysis (6260.95 ± 1181.90 W), (Cormie 2007a), (Cormie 2007b) and (Hori 2007). It is suggested that this may be due to differences in COM movement recorded by the force platform and bar movement. The use of a single LPT is also considered to be of limited validity for collection of displacement-time data in some free-weight exercises due to their inability to ascertain both horizontal and vertical displacement (Hori 2007). In such cases it has been recommended that two transducers be used in a triangular formation with the bar with the single apex at the bottom (Cormie et al 2007). However, rotation of the bar would still produce inaccurate results.

3.6.4 Accelerometers

The development of smaller, portable sensors has led to the possibility of increased testing environment flexibility. Motion sensors currently in use include pedometers and accelerometers. These devices may be used for purposes of surveillance, clinical, research and program evaluation (Tudor-Locke and Myers 2001). The use of accelerometers in athletic performance monitoring has been validated by numerous studies covering a range of disciplines including: ambulatory measurements (Bussmann et al 1998, 2001); physical activity (Bao and Intille 2004, Lee et al 2003 and Ravi et al 2005); gait analysis (Levine et al 2005); orientation and movement (Luinge 2002, Roetenberg 2006, Luinge and Veltink 2005, Luinge et al 2007, Lynch et al 2005 and

Roetenberg et al 2007); and to improve athlete performance (Anderson et al 2002 and Callaway et al 2009).

To provide a basic overview of how an accelerometer can be used to detect and characterise movement within a gym environment, the operation of an accelerometer is explained using the analogy of a ball placed inside a box. The box walls represent the axes of a tri-axial accelerometer with each axis assigned to a pair of walls. If the box was in a place with no gravitational field, the ball would float in the middle as illustrated in Figure 3.15(A). If the box was pushed to the left with an acceleration of 1g (9.81m/s^2) the ball would hit the –x wall and an output of -1g would register on the x axis (Figure 3.15(B)). The accelerometer detects a force that is directed in the opposite direction of the acceleration vector referred to as the inertial force.

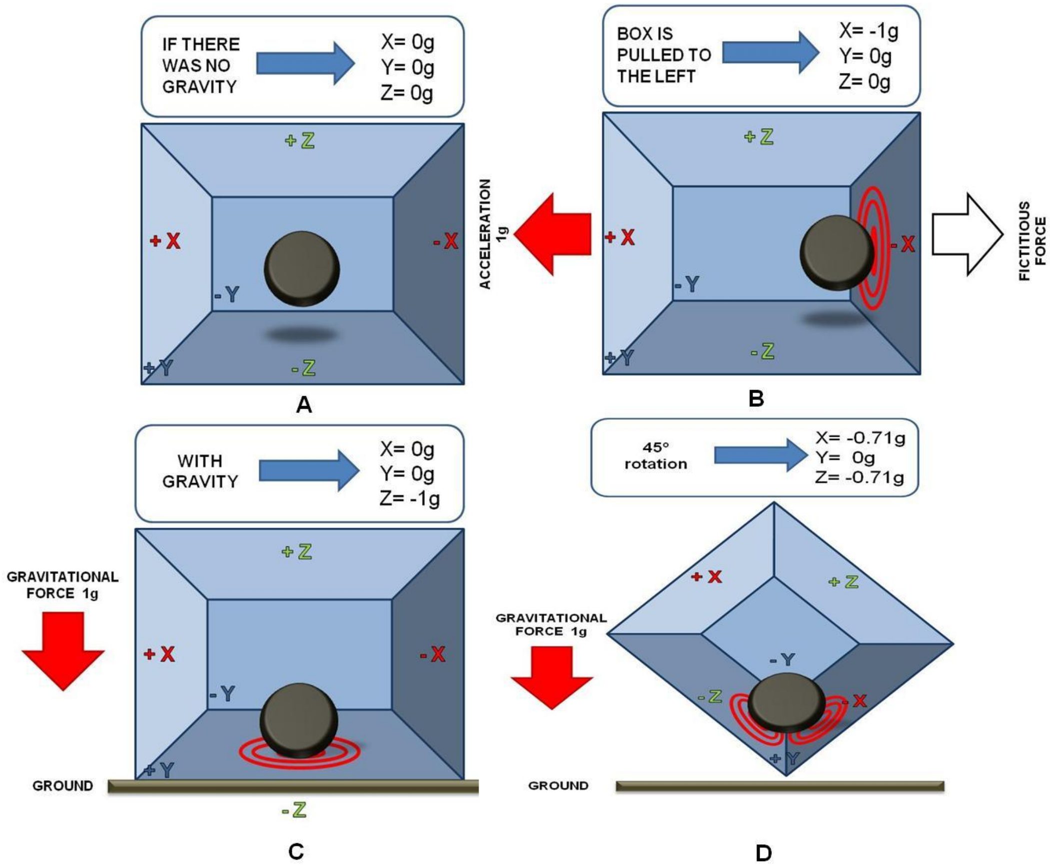


Figure 3.15 Box and ball analogy to demonstrate how a tri-axial accelerometer detects acceleration indirectly through forces applied to the device.

The analogy of an accelerometer in Figure 3.15 measures acceleration indirectly by monitoring a force that is applied to the system walls that is not necessarily a physical acceleration. For example, if the box is placed in a gravitational field, the ball would fall onto the –z wall, applying a force of -1g to the bottom wall as presented in Figure 3.15(C). Therefore an output of -1g would be read on the z axis even when the box is stationary. Tri-axial accelerometers are used to detect inertial forces on three axes. If the sensor (in Figure 3.15(D)) was rotated 45 degrees, the ball would touch the -Z and -X walls. Therefore a component of gravity and/or acceleration would be present in both axes. Whilst this analogy is useful for understanding how the accelerometer interacts with outside forces, it is more practical to fix the coordinate system to the accelerometer axes as illustrated in Figure 3.16. The R vector is the resultant inertial force measured by the accelerometer with Rx, Ry and Rz respectively denoting the projections of the R vector on the X, Y and Z axes. To calculate the value of the resultant inertial force produced by individual accelerations experienced by each axis, the Pythagorean Theorem is used:

$$R^2 = Rx^2 + Ry^2 + Rz^2 \quad \textbf{(Eq. 3.1)}$$

Manipulation of this theorem enables the vector to be calculated using the x, y and z acceleration output. The following equation is therefore required to calculate the magnitude of the R vector:

$$R = SQRT\,(Rx^2 + Ry^2 + Rz^2) \quad \textbf{(Eq. 3.2)}$$

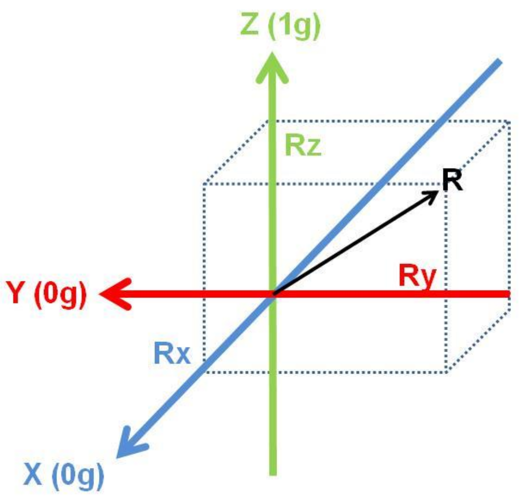


Figure 3.16 Fixing the accelerometer axes to the coordinate system and calculation of the R vector using Pythagorean Theorem.

The box-ball analogy demonstrates how the orientation of the accelerometer heavily influences the output. To prevent misinterpretation of the accelerometer output the type of movement corresponding to each axis must be identified. Perfect alignment with the *global reference frame* corresponds to

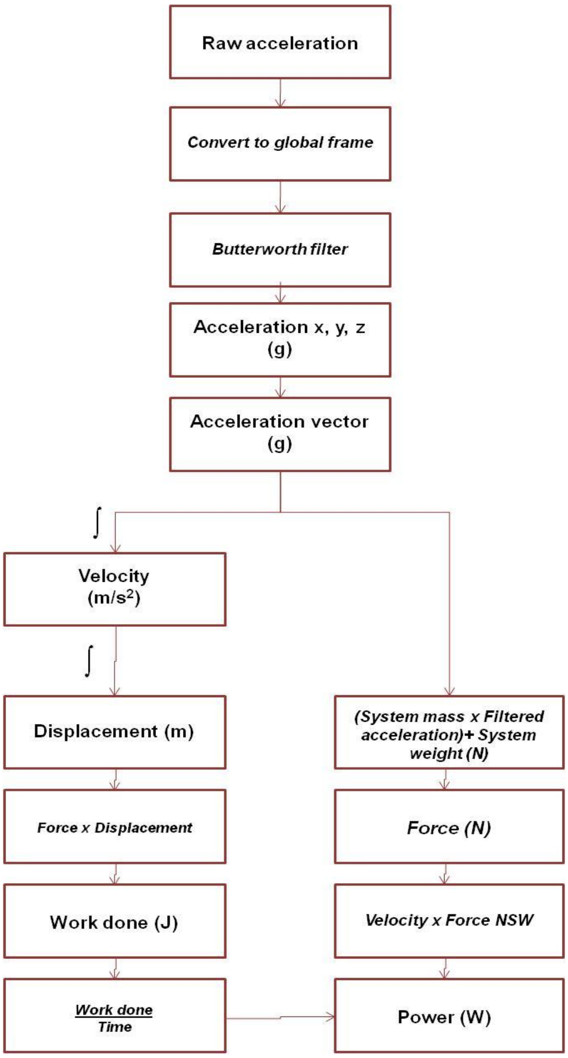


Figure 3.17 The calculation of kinematic data from raw accelerometer data.

when two axes are parallel to the floor and one perpendicular to the floor. The axis perpendicular to the floor experiences a component of gravity and therefore experiences an acceleration of 1g. Subsequent motion analysis requires correction for the gravitational contribution. The remaining two axes do not experience a component of gravity and therefore when stationary output 0g. The calculation process to derive acceleration, velocity and power from the acceleration data is presented in Figure 3.17. Sensors comprising three axis accelerometers alone attached to bars and athletes measure the linear acceleration of the system in the inertial reference frame (sometimes referred to as the "body reference frame" and not the global reference frame) (Woodman 2007). Directions can only be measured relative to the moving system (the accelerometers are fixed to the system and rotate with the system, but are not aware of their own orientation). Calculating the initial orientation and being able to continually monitor the orientation of the device throughout a movement requires move advanced technology (i.e three axis gyroscopes) that enables the accelerometer axes in the body frame to be translated into the global reference frame.

3.6.5 Wireless Inertial Measurement Units (WIMUs)

An inertial measurement unit (IMU) is an electronic device that measures acceleration, velocity, orientation and gravitational forces, using a combination of accelerometers and gyroscopes (Titterton 2004). An IMU that transmits wirelessly to an analysis visualisation and storage system is referred to a Wireless Inertial Measurement Unit

(WIMU). A gyroscope is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum (King 1998). A gyroscope is a spinning wheel or disk with the ability to take any orientation providing a more direct measure of rotation in a compact space (Benbasat 2000). Although this orientation does not remain fixed, it changes in response to an external torque. An IMU works by detecting the current rate of acceleration using one or more accelerometers, and detects changes in rotation using one or more gyroscopes. Such technologies would allow the rotation experienced (i.e changes in angular velocity around three orthogonal axes α, β, φ in which angular displacement is achieved via integration of the angular velocities) during an exercise to be monitored and accounted for, increasing the accuracy of the resultant kinematic data. However, the combination of technology and need to monitor the angle change is reliant upon the ability to calculate the *initial angle* and filtering of both gyroscope and accelerometer data. Therefore the amount of processing required to derive accurate results is increased.

3.6.5.1 Importance of the initial angle

Errors in orientation cause incorrect projections of acceleration signals onto the global axis (Woodman 2007). Gyroscopes only measure the angular velocity from the initial position and failing to determine the initial orientation means that it is not possible to determine the position of the device with respect to the global axes. When an IMU is stationary and perfectly aligned with the global frame the X, Y and Z accelerometers should read 0G, 0G and 1G respectively. The axes for acceleration and directions of positive rotation for the IMU are illustrated in Figure 3.18. As the device deviates from this orientation in the body frame, the axes need to be transformed to the global frame.

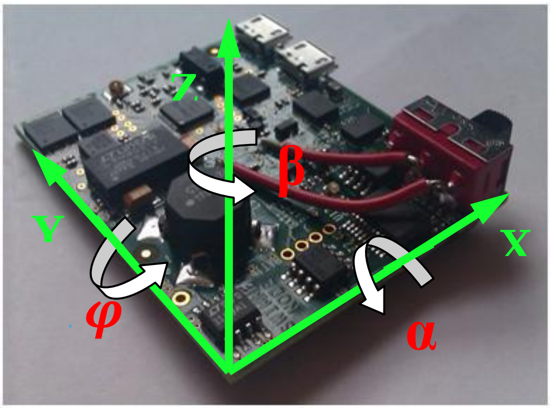


Figure 3.18 The axes of acceleration and directions of positive rotation.

3.6.5.2 The transformation matrix

A transformation matrix is required to return the accelerations in the body frame to accelerations in the global co-ordinate system to enable compensation for the component of gravity to be applied to the data. Secondly, determination of the 3D acceleration vectors (magnitude plus angles) is vital for accurate post session analysis and performance tracking.

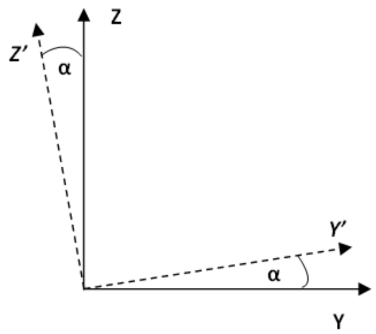


Figure 3.19 An example of the positive rotation about the x axis to

There are three common methods for transforming the accelerations: (1) Euler angles, (2) Direction Cosine Matrix and (3) Quaternions (Titterton and Weston 2004). To construct the 3D transformation matrix, two dimensional rotation is first considered around each of the respective axes. An example of the positive rotation about the x axis is presented in Figure 3.19. Resolving around three axes results in the following equations:

$$X = x'$$

$$Y = y' * \cos\alpha - z' * \sin\alpha$$

$$Z = z' * \cos\alpha + y' * \sin\alpha$$

Where x′, y′ & z′ are the local components of acceleration and X, Y & Z are global components of acceleration. These equations can then be represented in the matrix form presented below:

$$\boldsymbol{2D\ Transformation\ around\ X - Axis,}\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} * \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

The same technique can be applied to rotations around the Y & Z axes, giving the following equations:

$$\boldsymbol{2D\ Transformation\ around\ Y - Axis,}\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\varphi & 0 & \sin\varphi \\ 0 & 1 & 0 \\ -\sin\varphi & 0 & \cos\varphi \end{bmatrix} * \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

$$\boldsymbol{2D\ Transformation\ around\ Z - Axis,}\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

The highlighted 3x3 matrices are the transformation matrices [X], [Y] and [Z] respectively. The 3D transformation matrix is then calculated by multiplying these three matrices. Since the matrices are non-symmetrical, the order of multiplication is important. There are 6 possible combinations (XYZ, XZY, YXZ, YZX, ZXY, and ZYX). The equation below represents the 3D transformation matrix [XYZ], cosine is denoted by C and sine by S.

$$[XYZ] = \begin{bmatrix} C\varphi C\beta & -C\varphi S\beta & S\varphi \\ S\alpha S\varphi C\beta + C\alpha S\beta & -S\beta S\alpha C\alpha + C\alpha C\beta & -S\alpha C\varphi \\ -S\varphi C\alpha C\beta + S\alpha S\beta & S\varphi S\beta C\alpha + S\alpha C\beta & C\alpha C\varphi \end{bmatrix}$$

For small angle measurement, some assumptions can be made to decrease processing time (Titterton 2004).

- Cos(θ) ≈ 1
- Sin(θ) ≈ 0
- A function multiplied by another function (e.g. Sin(θ)* Cos(θ)) ≈ 0

A summary of the transformation matrix is presented in Table 3.8 (Gordon et al 2011), whilst the combination of the gyroscope and accelerometer signal through double integration to derive velocity and position is presented in Figure 3.20 (Woodstock 2007).

$$[XYZ] = \begin{bmatrix} 1 & -\beta & \varphi \\ \beta & 1 & -\alpha \\ -\varphi & \alpha & 1 \end{bmatrix}$$

Axis of Rotation	Equations	Transformation Matrix
X	$z'cos\alpha + y'sin\alpha = Z$ $y'cos\alpha - z'sin\alpha = Y$ $x' = X$	$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} * \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$
Y	$z'cos\varphi - x'sin\varphi = Z$ $y' = Y$ $x'cos\varphi + z'sin\varphi = X$	$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\varphi & 0 & \sin\varphi \\ 0 & 1 & 0 \\ -\sin\varphi & 0 & \cos\varphi \end{bmatrix} * \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$
Z	$z' = Z$ $y'cos\beta + x'sin\beta = Y$ $x'cos\beta - y'sin\beta = X$	$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$

Table 3.8 Summary of a 2D and 3D transformation matrix required to transform the WIMU to correspond with the global frame.

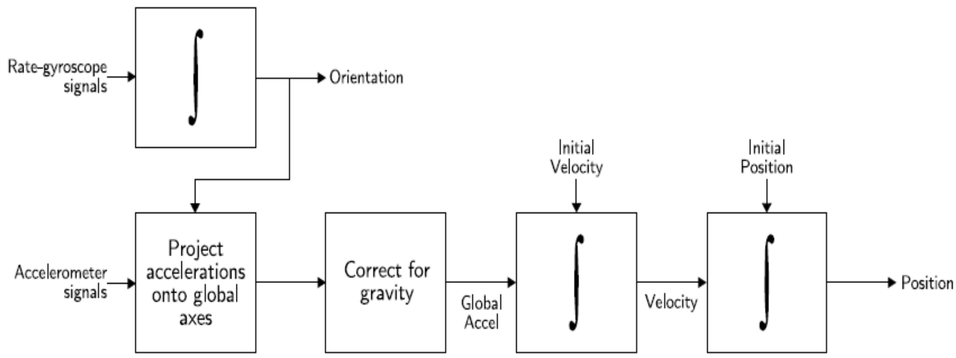


Figure 3.20 Inertial Navigation System (INS) algorithm designed to combine gyroscope and accelerometer data (Woodman 2007).

3.6.6 Commercial products currently available in the resistance training domain

The three main products currently available on the market to monitor performance in the resistance training domain are listed below.

1. Tendo Weightlifting Analyser (Tendo Sports Machines© 2005),
2. Myotest Pro (Perform Better© 2010),
3. MuscleLab Power (Ergotest Innovation© 2010).

The Tendo Weightlifting Analyser (Tendo Sports Machines, 2005) is based on the attachment of a wired weightlifting bar or athlete's body and uses a velocity sensor unit and a microcomputer to provide real time data of peak power, peak velocity, average power and average velocity. The velocity sensor consists of an optical sensor with light source with slotted disk for displacement and time measurement and a DC motor for movement orientation (Tendo Sports Machines, 2005). This restricts its capability to only measuring linear movements accurately and thus exercises requiring movement away from the midline of the body will generate less accurate results. The manufacturer states the error associated with the system is less than 3% suggesting this is sufficient precision for training equipment. However, only a linear exercise using a cable pulley system (a lat pull down machine that is not free weight based) was investigated and the effect of rotation was not considered (Tendo Sports Machines, 2005). The system is attached to the barbell by means of a special Kevlar cable with a Velcro strap at the end. The data obtained can be displayed in real time or transferred to the supplied computer software for post analysis.

MuscleLab Power (Ergotest Innovation© 2010) is based on the same concept as the Tendo Weightlifting Analyser, however it provides a more in depth analysis by estimating a one-repetition maximum lift (1-RM) at lighter loads. In contrast to the Tendo unit, MuscleLab power does not have any integrated display to transfer data for real time analysis.

The Myotest Pro (Perform Better© 2004) uses a tri-axial accelerometer. The acceleration data is integrated to calculate velocity force and power output. The manufacturer of Myotest Pro claims that it can accurately estimate 1RM at lighter loads. However most of the athletes will be interested in calculating 1 RM at high loads, whilst the system only monitors seven different pre-programmed exercises. Pre-programmed exercises can lead to an inaccurate indication of performance. The product assumes the movement profile to follow pre-programmed paths and neglects the variations due to the actual body movement, leading to an inaccurate power output. A recent study conducted by Houel (2011) investigated the validity of the Myotest Pro in comparison to a force platform in calculating take off velocity and time to peak velocity. The results indicated an error of 0.8 m/s^2 and 0.03 s respectively. The authors concluded that the Myotest Pro could only be used to estimate velocity of the COM and cannot be used to estimate other kinetic variables.

Although this product utilises accelerometer technology, the accuracy of the system is compromised as it does not account for any rotational errors that will be present in any but the simplest training profiles. Consequently, the orientation of the bar cannot be determined when the device is accelerating. A product validation study also conducted using the Myotest Pro, similarly failed to address the issue of rotation (Jidovsteff 2008). Therefore it is clear that the application of combined accelerometer and gyroscope data to produce a Wireless Inertial Measurement Unit (WIMU) is not a well researched area within the resistance training domain. A review of the technology commercially available is presented in Table 3.9. The results indicate that although real time analysis is available, the accuracy of the performance data output is compromised by neglecting the effect of bar rotation and independent movement of the bar from the body during non-linear exercises.

Criteria	Tendo Weightlifting Analyser (Tendo Sports Machines, 2010)	MuscleLab Power (Ergotest Innovations, 2010)	Myotest Pro (Perform Better, 2010)
Power	✓	✓	✓
Velocity	✓	✓	✓
Force	X	X	✓
Distance	✓	✓	✓
Profile	X	X	✓
Accelerometer	X	X	✓
Velocity sensor	✓	✓	x
Real time display	✓	X	✓
Bar rotation	X	x	x
Analysis Software	✓	✓	✓
Internet based comparison	X	X	✓
No. of components	2	2	1
Battery	✓	✓	✓
Bar	✓	✓	✓
Wrist	X	X	x
Back	✓	X	✓
Resistance machines	✓	✓	✓
RRP	£996 (Tendo Sports Machines, 2010)	£990 (Ergotest Innovations, 2010)	£927 (Myotest 2010)
Market Focus	Recreational and elite	Elite	Sports professionals

Table 3.9 Comparison of performance monitoring products within the resistance training domain.

3.6.7 Current monitoring technology summary

A summary of current technology within the resistance training domain is presented in Table 3.10. Accelerometers and WIMU's are not yet well utilised in the resistance training domain. Most studies have focused on the validation of such technology through comparative analysis combining video, force platform and LPT technology (Cormie 2007, Hori 2006, Chui 2004, Cronin and Henderson 2004 and Rahmani 2001). Recent studies focus on the relative and absolute validity of kinetic and kinematic data derived from video, force platforms, LPT and sensor technology. Whether using one form of technology in isolation or combining technology influences the derived kinetic and kinematic data is an area of increasing interest (Cormie 2007).

Technology	Technology summary
Video technology 	• Real time feedback is not available. • Restricted to the elite level. • Unsuitable for a gym environment. • Video may not provide the athlete with sufficient understanding of the changes in movement. • Digitisation is time consuming. • Human error during digitisation process. • Increased cost of high speed cameras for rapid movement analysis. • A skilled user is required for the analysis. • Disruptive to training. • It is suggested that all these methods are disruptive to training time due to the set up, analysis procedure and post session analysis. • Reducing the training session disruption is a major area for development. (Bruenger 2007). • Visual evaluation of a lift is difficult for explosive movements where a poor angle, obscured body position due to the plates and considering all phases of the movement can restrict the amount of feedback that can be given. (Bruenger 2007). • Rapid movement of the bar can be difficult to follow (Bruenger 2007). • Required to characterise movements in relation to other kinetic and kinematic variables- aids signal processing for other methods of analysis.
Force platform technology 	• Real time feedback is not available. • Heavy post processing is required. • Expensive to implement when vertical and horizontal movement is analysed. • Trajectory of the barbell cannot be determined. • Skilled user required to perform post analysis. • Difficult to implement multiple force platforms in a gym environment. • Integration error increases as more kinematic variables are calculated. • Best indicator of force generated by whole body.
LPT technology 	• Real time feedback is not available. • Analysis is limited to either peak values or requires subsequent software analysis through post processing. • More suited to a gym environment than video or forceplate technology. • Accuracy is reliant upon only one LPT disregarding horizontal displacement which disregards one of the main aspects of weightlifting- the trajectory of the barbell. • Restricted to linear movements. • Skilled user required to perform post analysis. • Multiple use of the technology is limited in a gym environment. • Multiple transducers can be used to monitor vertical and horizontal movement, increasing post analysis.
Accelerometer and WIMU technology 	• There is a distinct lack of research in this area. • Uncertainty regarding accuracy. • Uncertainty regarding the application to a variety of lifts. • Lack of research using inertial measurement unit. • Optimum location is unknown. • Lifts that experience rotation can alter the accuracy of results.

Table 3.10 Summary of video, force platform, linear positional transducer, accelerometer and WIMU technology.

3.7 Current integrated monitoring research

Whether direct kinetic or kinematic methods are used, the data are often combined and compared to improve performance understanding. Earlier research was focused on the use of video technology to monitor training outputs, however, recent methods have combined kinetic and kinematic methods to either gain more data or to compare the accuracy of the technologies. The calculation of performance variables can vary according to the type of technology used and resultant calculation methodology as discussed in the following sections.

3.7.1 Comparing force platform and LPT technology

Currently, there are four main methods used in the resistance training domain to determine power output (Dugan et al 2004). These four methods have since been investigated in relation to weight lifting specific exercises to determine the overall applicability and specificity of the feedback gained (Hori et al 2006a). An overview of each method is presented in Table 3.11. Each method is discussed briefly in relation to the squat jump to identify which provides the most accurate result. The Ground Reaction Force (GRF) of a squat jump was measured using a force platform and these data combined with bar displacement data collected using a positional transducer (Dugan et al 2004). Power output was calculated using one of the four outlined methods, two that utilise inverse dynamics to calculate kinetic data from kinematic data, one that utilises forward dynamics to calculate kinematic data from kinetic data and a one final method that combines force platform and transducer data to obtain kinetic and kinematic data (Hori et al 2006a).

	Methods for measuring power output			
	Method 1	**Method 2**	**Method 3**	**Method 4**
Equipment	Position transducer	Position transducer	Force platform	Force platform and Position transducer
Method	Barbell + Lifter mass	Barbell	Barbell + Lifter's mass	Barbell + Lifter's mass
Velocity	Barbell displacement and known sampling rate	Barbell displacement and known sampling rate	Acceleration from force, velocity from acceleration if initial velocity is 0.	Barbell displacement and known sampling rate
Acceleration	Velocity and known sampling rate	Velocity and known sampling rate	Force / Mass	N/A
Force	Mass x Acceleration	Mass x Acceleration	Force platform	Force platform
Power	Force x Velocity	Force x Velocity	Force x Velocity	Force x Velocity

Table 3.11 Methods for measuring power output during a lift (Hori et al 2006a)

3.7.1.1 Method 1:

This method uses a single LPT and assumes that the displacement of the centre of gravity (COG) of the calculated mass (the barbell and lifter) is the same as the barbell alone (Dugan et al 2004). Assuming that that COG for both the lifter and barbell is the same will yield inaccurate results particularly for exercises where the relative motion of the bar and body differ significantly. For example, the trajectory and resultant movement of the bar during a power snatch or power clean does not match that of the body.

3.7.1.2 Method 2:

This method utilises the same calculations and technology as method 1, however, the lifter mass is not included. Although this overcomes the inaccuracy in assuming the lifter and barbell COG can be represented as one, the resultant power output value is be significantly lower than values obtained from methods 1,3 and 4. It is only the power being applied to the barbell that is being considered, power output of the leg and trunk extensors being applied to the ground is disregarded (Dugan et al 2004). Nonetheless, this method can be applied to a variety of weightlifting exercises in which the barbell COG and lifter COG do not match. It is suggested however, that this method be applied to upper body isolated movement, therefore power is not being generated in the lower body.

3.7.1.3 Method 3:

This method determines the GRF at regular time intervals using a force platform, whilst applying the forward dynamics approach through integration of force-time data (Dugan et al 2004). This approach requires the initial velocity at the start of data collection to be zero (Hori et al 2006a). Consequently, this method may have to be restricted to exercises which do not start from the floor as the overall mass of the system will change as the bar is lifted. Only movements that are started from the knee or mid thigh and above may be suitable and this limits the exercise applicability vastly in weightlifting, as many of the key training exercises from standing involve execution from the floor. Furthermore, the integration process magnifies any slight errors within the force calculation resulting in erroneous velocity and power results (Wood 1982).

3.7.1.4 Method 4:

Similarly to method 3, force is calculated directly from a force platform in method 4. However, velocity is calculated from barbell displacement using a single LPT. Again, since the lifter and barbell mass are included, this results in the same issues as method 1, in which the COG of the barbell is thought to represent that of the lifter. Displacement is measured directly providing an improved approximation of barbell velocity, however, this method is limited to exercises in which the barbell moves with the lifter's body.

Combining kinetic (force platform) and kinematic (LPT) data is a natural progression to investigate further the measurement of power. Research has been conducted to compare single LPT and force platform technology and a new method utilising two single LPT's (Cormie et al 2007). The results indicate that methods relying upon kinematic data alone (displacement) either over estimated the power output (as seen with one LPT (6496 W ± 1135 W) or two LPT's (6404 W ± 1168 W) or underestimated power output (when one LPT was combined with the constant mass (3379 W ± 505 W)) in comparison to the power derived from a combined kinetic and kinematic system (2 LPT's and force platform (6332 W ± 1085 W)). When using one LPT and calculating the force as a constant, acceleration of the system mass is not considered and resultant power output is significantly lower (Cormie et al 2007, Baker 2001, Coelho et al 2003a, Coelho et al 2003b and Jennings et al 2005).

Alternatively, kinetic methods utilising only a force platform have shown an under estimation of velocity and power output, particularly where the bar is required to move independently of the body (Rahmani et al 2001) (GRF was 23% lower than the displacement method). It is suggested that the reliance upon a single LPT to obtain kinetic information increases ambiguity (Cormie 2007). The reliance upon the inverse dynamics approach requires a great deal of data manipulation and as with kinematic methods, double differentiation of position to determine acceleration increases noise and inaccuracy (Wood 1982).

3.7.2 Comparing accelerometer, force platform and LPT technology

Recent research has focused on the use of accelerometers to provide the same kinematic data as a transducer or video technology through the use of forward dynamic calculations. It is suggested that an accelerometer may be a reliable and versatile way to assess power (Thompson and Bemben 1999). Studies that compare the performance variables derived from an accelerometer attached to the bar to other kinetic and kinematic methods are less common. In contrast to video, force platform and LPT technology, only six studies investigating the application of accelerometers to free weight training have been conducted (Sato 2009, Thompson and Bemben 1998, Manne 2006, Chang 2007, Heoul 2011 and Crewther 2011). A recent study conducted by Crewther (2011) compared accelerometer output to single LPT and force platform data to determine the relative validity (defined as the correlation between both datasets). Relative validity values between 0.85-0.99 have been documented. However, comparison of LPT and accelerometer application has shown higher accelerometer-force platform correlation (0.85-0.99) than LPT-force platform correlation (0.59-0.87), (Crewther 2011). This suggests that linear movement of the bar is more accurately monitored using accelerometer technology than LPT technology.

Other studies focusing on the use of acceleration sensor technology within the resistance training environment have been documented by Sato et al (2009), Manne et al (2006) and Chang et al (2007). Sato et al (2009) investigated the acceleration experienced during a clean and snatch using a tri-axis accelerometer mounted on a barbell to investigate the effect of peak acceleration values on force production, whilst Manne (2006) investigated the acceleration during a bench press using a wrist mounted three-axis accelerometer to determine energy expenditure. This area was investigated further by Chang et al (2007) who examined the use of sensors located on both the wrist and hip, two sensors were used to aid the identification of different lifts. This study examined nine different exercises to target the arms, upper body and lower body. An overview of each is presented in Table 3.12. The aim of this study was to determine whether the number of reps and type of exercise could be determined from the acceleration signal. The error in number of repetitions identification was between 5-15%, this was based on the repetition count only as the study did not investigate the calculation of other kinematic variables from the acceleration data. Furthermore, the results in Table 3.12 indicate that in Changs et als (2007) study does not investigate whole body movements that cause multi-planar movement. Therefore, the path tracked by the load is predominantly linear, whilst each exercise has a relatively short movement path to restrict rotation. Chang et al (2007) also suggests that rotation does not affect the results which can only be true for linear movements. However, whole body, multi-planar movements such as the clean or snatch cause higher rotations of the bar and ignoring rotation will cause significant error when analysing the data. Despite investigating the clean and snatch, Sato et al (2009) does not discuss the effect of rotation upon the acceleration. Therefore the validity of the results is questionable.

Exercise	Muscle movement	Muscle group	Path of load	Plane
Bicep curl	Isolated	Biceps	Arc	Sagittal
Tricep curl	Isolated	Triceps	Arc	Sagittal
Bench press	Compound	Chest	Linear	Sagittal
Fly	Isolated	Chest	Arc	Transverse
Bent over row	Compound	Upper back	Linear	Sagittal
Lateral raise	Isolated	Shoulders	Arc	Frontal
Shoulder press	Compound	Shoulders	Linear	Frontal
Standing calf raise	Isolated	Calves	Linear	Frontal
Deadlift	Compound	Legs, lower back	Linear	Frontal

Table 3.12 An overview of the exercises investigated by Chang et al (2007) using an accelerometer

Despite the limitations, the application of accelerometers to the resistance training domain could facilitate the development of real time feedback during a session. In contrast to video, force platform and LPT technology, few studies applying accelerometers to free weight training have been conducted, the limitations could therefore stem from the lack of research within the domain. The potential to improve monitoring of training inputs through automatic recognition of the number of repetitions completed, whilst providing training output data during a session could provide significant benefits to current resistance training monitoring. The major advantages of an accelerometer based solution include the low cost, ease of use with minimal training session disruption and scalability.

As identified by numerous researchers, the need for kinetic and kinematic data is essential to understanding performance (Cormie 2007, Houel 2011 and Hori 2006), therefore, considering the forces generated and the kinematics of the body and barbell would provide the greatest knowledge of performance. Research that combines the use of accelerometers and force platforms has not been well investigated to derive kinetic and kinematic data. Using a single LPT does not account for the horizontal displacement or rotation of the bar, using 2 LPT's monitors the horizontal and vertical movement of the bar but does not account for rotation. Monitoring barbell acceleration as an indicator of performance has only been investigated by four studies (Sato et al 2009). Failing to account for bar rotation or multi-planar independent movement of the bar limits the range of exercises that can be monitored to linear exercises. Combining force platform data to monitor body movement and accelerometer and gyroscope technologies to monitor bar movement (accounting for rotation) is an area that requires further research.

Evaluation of previous and recent research has identified the most commonly investigated performance variables, exercises and method of analysis. A summary of the research conducted in the resistance training domain and corresponding limitations is listed in Table 3.13. The results suggest that there is a clear need in the resistance training domain for the development of an integrated system with a user friendly interface that stores the training inputs and outputs to improve how individuals monitor performance. Most research has focused on the squat jump, clean, pull and snatch. Although these exercises are key to a weightlifter, investigation into supporting exercises completed in training would be beneficial in monitoring training techniques to target a wider range of users. Therefore, development of a real time application utilising accelerometer, gyroscope and force platform technologies would support performance analysis in the resistance training domain.

Method	Authors	Research limitations
Single transducer	Alemany, 2005, Baker 2001, Baker and Nance 1999, Hori 2006, Bourque and Sleivert, Cronin and Henderson 2004, Esliger and Sleivert 2003, Falvo 2005, Izquierdo 1999, 2001, 2002, Rahmani 2001, Siegal 2002, Thomas 1996, Weiss 2004, 2005 and Cormie 2007.	Inaccurate representation of barbell trajectory (as horizontal displacement is not considered), inaccuracies during double differentiation.
2 transducers	Cormie 2007.	Inaccurate representation of barbell trajectory (as horizontal displacement is not considered), inaccuracies during double differentiation.
Forceplate	Hori 2006, Dugan 2004, French 2004, Haff 1997, Iossifidou 2005, McBride 1999, 2002, Sands 2005, Souza 2002, Kawamori 2005 and Cormie 2007.	Relies upon impulse momentum relationship. Method has to be applied to upper body movements- exercises cannot begin from the floor as initial velocity will not be zero. Expensive technology.
Forceplate and a single LPT	Hori 2006, Chui 2004, Cronin and Henderson 2004, Hori 2005, Rahmani 2001, Cormie 2007.	Barbell COG is assumed to be the same as the lifter COG. Velocity is determined from transducer displacement- horizontal displacement is not considered. Limited to exercises such as squat jump- in which COG of barbell and lifter is approximately the same.
Forceplate and a 2 LPT's	Khamoul 2009, Cormie 2007.	Same as the above case with a single transducer- Cormie 2007 compared against use of a single transducers reported no significant difference between the a single and two transducers.
Video and motion analysis software	Hori 2006, Gourgoulis 2000, Garhammer 1980 and Souza 2002, Salaami 2008.	Time consuming digitisation- limited to lab environment. Not immediate feedback.
3D Modelling	Nejadian 2008	Every athlete is individual, hard to apply to environment other than a lab
Accelerometers	Sato 2009, Thompson and Bemben 1998. Manne 2006, Chang 2007, Houel 2011.	Not enough research to determine accuracy, forwards dynamics may cause error in the calculations, area requiring further research due to the low cost and portability of such equipment. Sato only observed the high pull to eliminate rotation of the exercise which causes error in the data- this is not a realistic indication of many other exercises that clearly involve rotation of the bar.

Table 3.13 Summary of research conducted in the resistance training domain and corresponding limitations

3.8 Brief Chapter summary

TARGET OBJECTIVES:

- *Gain an understanding of exercise physiology to understand the effects of resistance training.*
- *Identify training inputs and outputs and determine which are most relevent to the resistance training domain.*
- *Identify the current monitoring techniques used within the resistance training domain and investigate the benefits and limitations of each..*
- *Identify the current gaps in research and technology development in the resistance training domain.*

The target objectives were achieved by separating this Chapter into subcategories. The first three objectives were targeted in three correspondong subcategories whilst the final objective was achieved via critical analysis. Each section is summarised according to the subcategory research questions, the resultant research gaps are outlined at the end of the Chapter, whilst a summary of the new knowledge as a result of the Chapter content is also provided.

3.8.1 Section 1: Resistance training overview

TARGET RESEARCH QUESTION:

What are the benefits of free weight resistance training and what types of adaptation occur as a result of resistance training?

There are many benefits to resistance training both health and performance oriented, all of which stem from the ability to produce force. Increased force production is reliant upon functional hypertrophy, the cross sectional area of the muscle is increased and muscle fibre growth is accommodated. Increased muscular strength and force production also impacts the ability to generate power, whilst the adaptation of muscle fibre type and pulmonary system can increase fatigue resistance. Physiological and neural adaptation of the muscle can be achieved by resistance training, the type of adaptation is dependent on the type of training undertaken, which is ultimately by the identified training goals. A summary of the key adaptations is presented in Figure 3.21. This overview identifies the four main training goals that can be achieved through resistance training; endurance, hypertrophy, strength and power. Targeting different forms of adaptation (endurance, hypertrophy, strength and power) is dependent upon controlling training inputs and acute variables that determine the training specificity and progression.

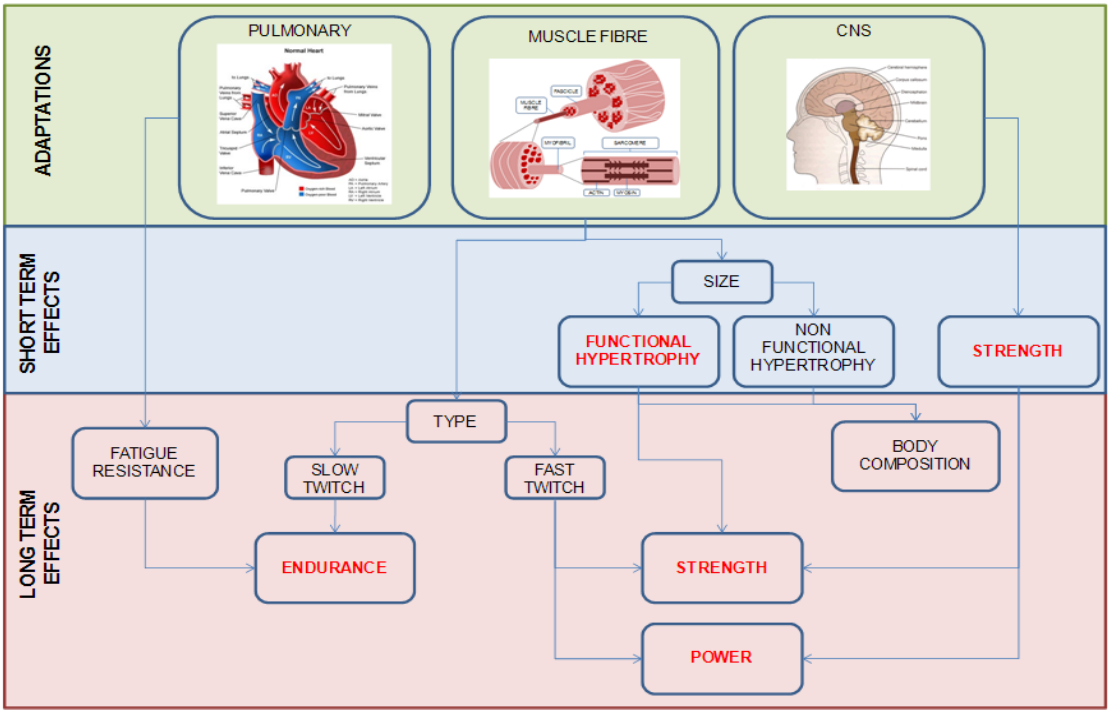


Figure 3.21 A summary of resistance training adaptations that impact endurance, hypertrophy, strength and power

3.8.2 Section 2: Training inputs

TARGET RESEARCH QUESTIONS:

How can training inputs be manipulated to train for endurance, hypertrophy, strength and power and how are training inputs monitored?

The extent and type of adaptation is dependent on the muscle actions, intensity, volume, exercise selection, exercise order, rest periods and frequency (Tan 1999). The FITT principle involves manipulation of the load, sets, reps and rest time to target four training systems: endurance, hypertrophy, strength and power. Manipulation of the acute variables to target each zone is presented in Figure 3.22. Progressive overload is required to improve performance and the structure of an overall program is based upon the principle of periodisation. Effectiveness of the training inputs is quantified by analysis of the training outputs. Monitoring training inputs is heavily reliant upon manual notation at the advanced, intermediate and novice level.

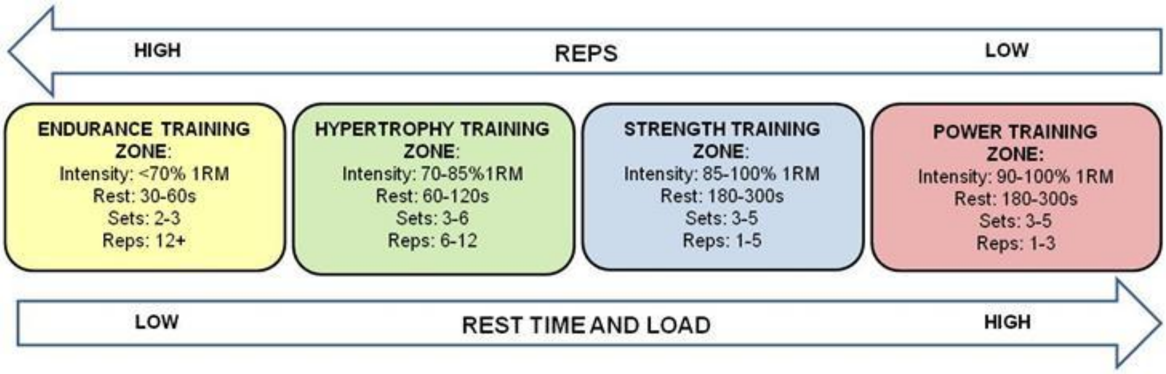


Figure 3.22 Review of acute variables to target endurance, hypertrophy, strength and power training.

3.8.3 Section 3: Training outputs

TARGET RESEARCH QUESTIONS:

Which training outputs are monitored within the resistance training domain and which training outputs have received most research focus?

A summary of the most commonly researched training outputs, exercise and method of analysis is presented in Figure 3.23. The results indicate that most research has focused on the the generation of peak force using force platform technology monitoring linear movement (squat jump). Technologies that can be implemented in a gym environment (LPT's and accelerometers) are not as well researched (ranked third from a possible four). There is a need for research investigate combining technologies to increase the accuracy and range of performance data that can be obtained (considering both linear and multi-planar movement in which the bar and body move independently).

Rank	Performance variable(s)	Exercise	Method of measurement
1st	Peak force	Squat Jump	Forceplate
2nd	Peak velocity and Peak power	Snatch/Power Snatch	Video
3rd	Bar trajectory	Bench Press	Transducers and Accelerometer
4th	Average power and acceleration	Clean	Optical encoder and 3D modelling
5th	RFD and RPD	Clean Pull	
6th	Average velocity		

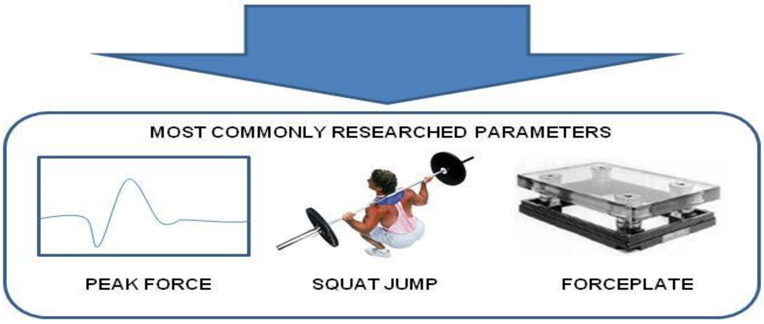


Figure 3.23 Identification of the most commonly researched performance variable and exercise.

3.8.4 Section 4: Current monitoring technology

TARGET RESEARCH QUESTIONS:

What forms of technology are currently used to monitor performance in the resistance training domain?

Video and force platform technology are most commonly used in a lab based environment for elite analysis. Commercial products available for both elite and recreational use more LPT and accelerometer technology. However, such systems do not accurately monitor a range of exercises due to neglecting the effect of rotation and non-linear trajectory paths. Combined gyroscope and accelerometer technology providing real time time, wireless feedback (WIMU) is required to account for rotational analysis but would not monitor body movement moving independently of the bar.

What are the limitations and resultant gaps in current research methods and technology development?

A summary of the current gaps in monitoring technology design are identified in Figure 3.24. These gaps outline the main technology inadequacies within the resistance training domain and overall need to improve performance monitoring systems. The limitations of previous studies and resultant gaps in research are identified in Figure 3.24. These gaps outline the type of research required to derive new knowledge. The limitation, research gap and corresponding Chapter targeting the research gap is presented in Figure 3.25. Conducting a thorough review of research in the resistance training domain and providing an overview of the resistance training fundamentals has highlighted numerous areas for improvement. The gaps in technology design identify the overall need to investigate real time analysis through a combination of kinetic and kinematic methods. There is a need for an integrated system to collect, analyse and communicate resistance training performance variables to a variety of users at an elite and recreational level. Therefore, the aim of this research is to investigate the development of a monitoring system that provides real time feedback in a free weight training environment primarily targeting elite analysis to ensure that a range of exercises are considered. A summary of the new knowledge gained as a result of the Chapter content is presented in Figure 3.26.

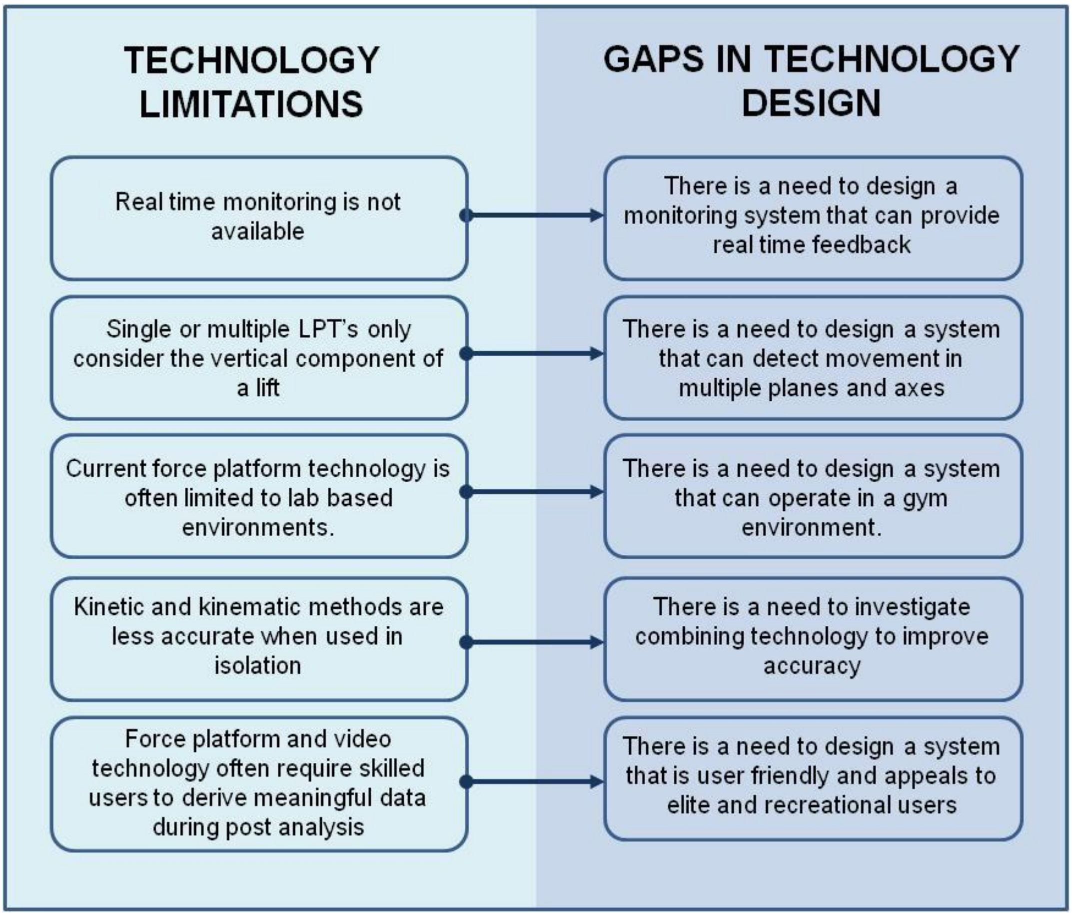


Figure 3.24 Identification of the technology related limitations and corresponding gaps in technology development within the resistance training domain.

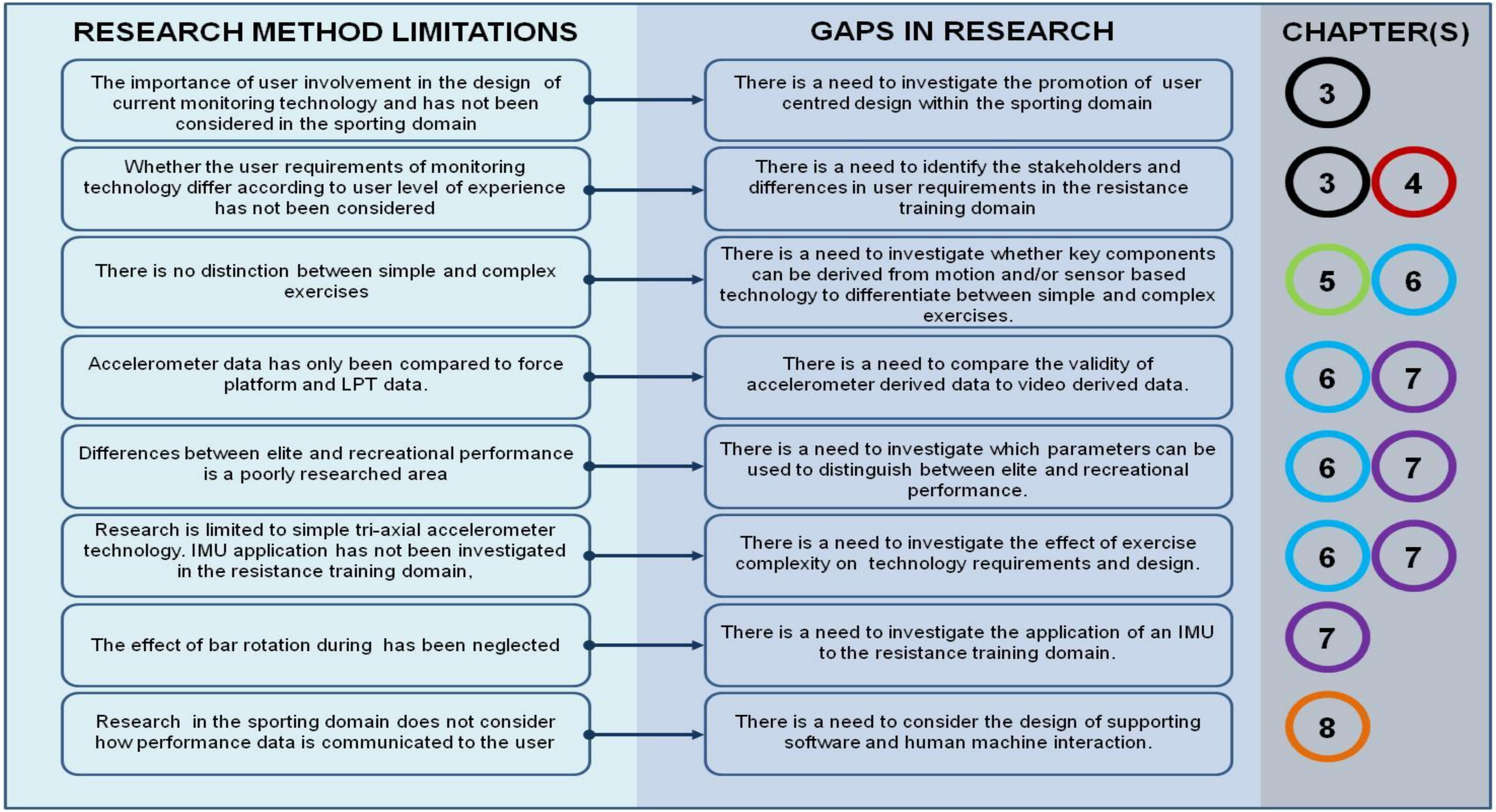


Figure 3.25 Identification of the current gaps in research conducted in the resistance training domain, the resultant gaps in research and corresponding Chapters that target each research gap.

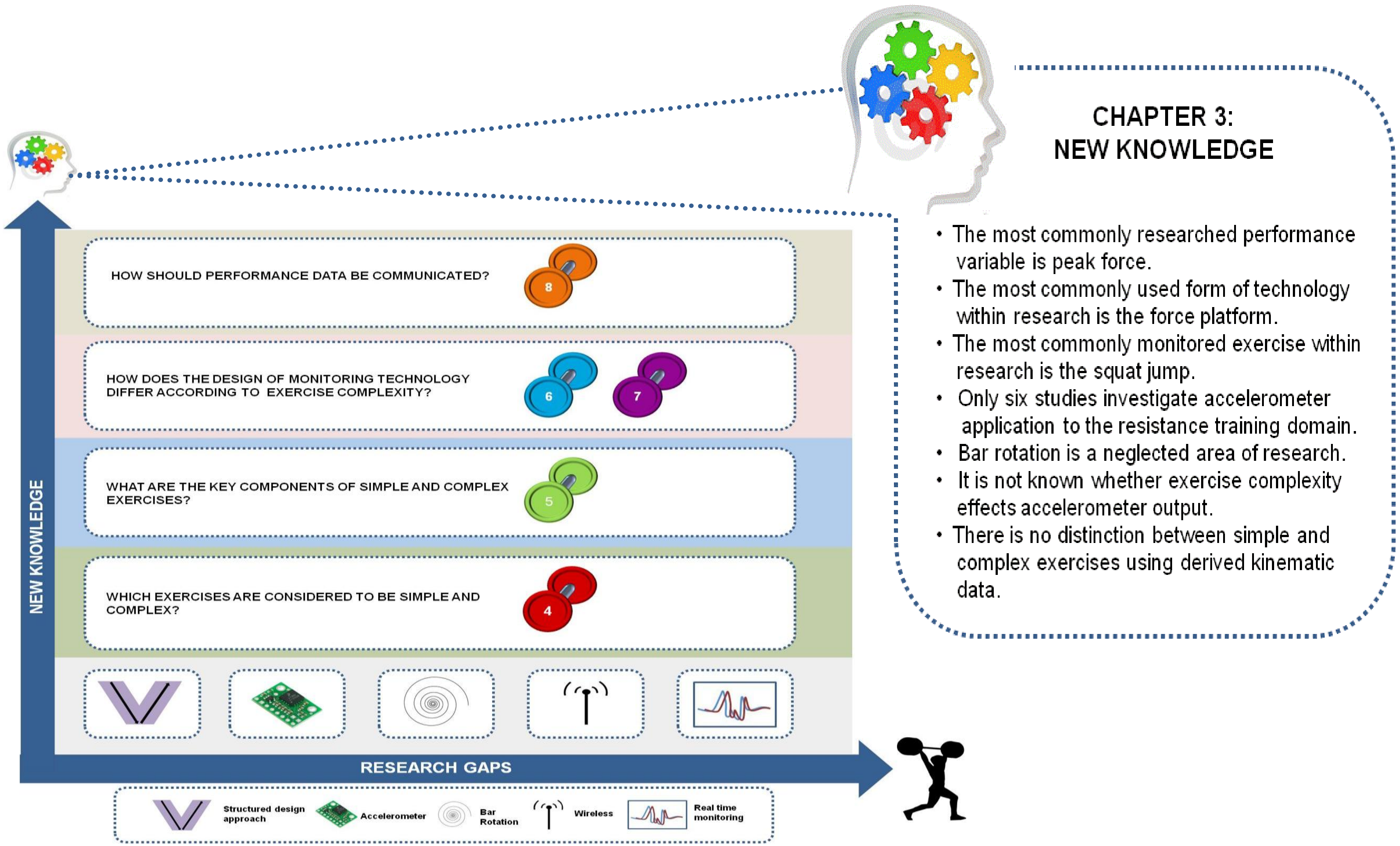
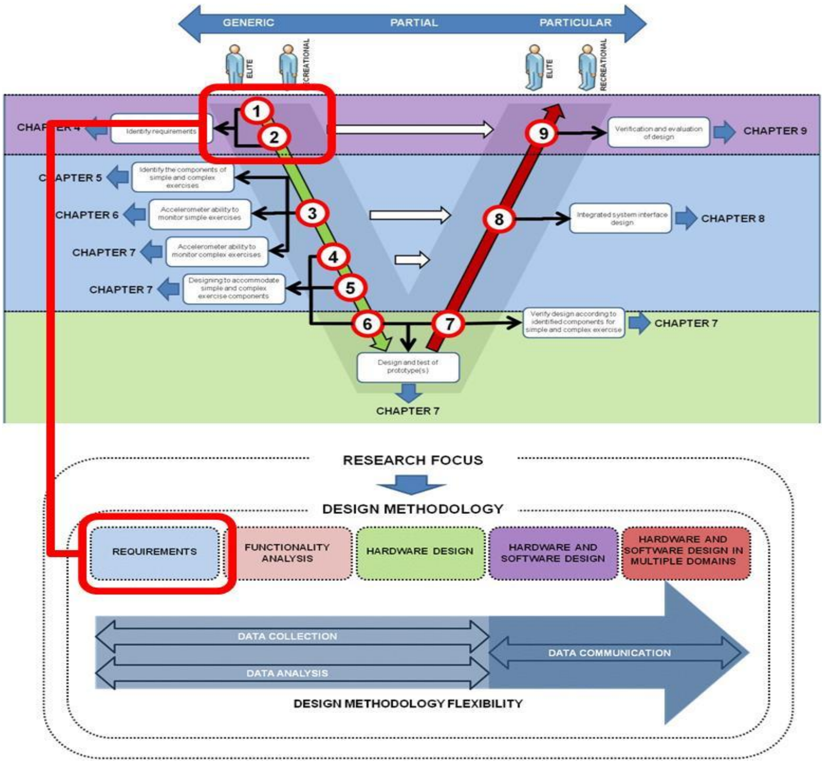


Figure 3.26 Core question findings; Lack of accelerometer and WIMU development to enable wireless communication, real time monitoring, and lack of corresponding research regarding the application of wireless, real time monitoring that accounts for bar rotation and the identification of new knowledge acquired as a result of the Chapter.



Chapter 4

4.0 Capturing user requirements

TARGET OBJECTIVES:

- *Collect both qualitative and quantitative data to define user requirements from an elite and recreational perspective.*
- *Re-iterate user requirements to consider user type and level of experience.*

TARGET RESEARCH QUESTIONS:

- *Which requirements elicitation methods should be combined to promote re-iteration of the user requirements?*
- *Which exercises are considered to be the most complex and which variables are considered to be most important for monitoring performance?*
- *How does user experience and gender affect the user requirements?*
- *How does re-iteration of the requirements elicitation methods affect the derived user requirements and what are the resultant user requirements?*

4.1 Introduction

The aim of this Chapter is to investigate the different techniques available for capturing user requirements and apply the most suitable methods to this research. Once the most appropriate techniques have been identified the objective is to collect data related to user's training behaviour, current monitoring techniques implemented in the gym environment, how users respond to the introduction of technology and whether opinions and behaviour differ according to user type and level. Identifying the performance variables of highest importance is a main focus of this research as this influences the type of technology that can be utilised and how data is presented to the user. The collection of user requirements is separated into two categories: (i) determining what data should be collected and (ii) how the data are presented to the user, considering both software and hardware development.

4.2 Requirements elicitation methods

Close involvement with users is the only way to define sufficient initial requirements (Monk et al 1993). Supporting research states that the design approach carrying the highest risk is the development of a product without user involvement (Weisberg and Lanzetta 1991). Statistical analysis has shown the benefit of user analysis:

- 80% of maintenance is due to unmet or unforeseen user requirements; only 20% is due to bugs or reliability problems (Pressman 1992).
- More than 30% of software development projects are cancelled before completion, primarily because of inadequate user design input (Standish Group 1995).
- The top two reasons projects fail is lack of user involvement and lack of requirements (Standish Group 1995).

Consequently, a major aspect of the proposed combined modelling approach is to achieve a detailed understanding of user requirements. There are several methods often utilised to obtain user requirements, however, it is not a simple process, since these requirements are likely to change during the development process (Goguen 1993). Defining requirements is a well researched area and is commonly referred to as requirements elicitation (Christel and King 1992). In requirements engineering, requirements elicitation is the practice of obtaining the requirements of a system from users, customers and other stakeholders (Somerville and Sawyer 1997). According to Zhang (2007), different stakeholders have distinct ways to store, recognize and express their knowledge about the problem domain. Several methods exist to capture requirements depending on the environment and system application. Each has an advantage over the other in terms of either simplicity, complexity and/or maturity (Jiang et al, 2007). The division of these methods according to the means of communication are identified in Figure 4.1 (Zhang 2007). However, it is suggested further by Zhang (2007) that a single method is unlikely to accommodate all stakeholders within a project.

Selection of the appropriate method(s) is dependent upon identifying what type of knowledge is required and how that knowledge is acquired from the users. Knowledge that is easily obtained from others is referred to as 'explicit' knowledge, whilst 'tacit' knowledge is harder to express and collect. According to Parsaye (1988) there are three major approaches to capture tacit knowledge from groups and individuals:

- Interviewing experts.
- Learning by being told.
- Learning by observation.

Obtaining both tacit and explicit knowledge therefore requires a combination of requirements elicitation techniques. A review of the four main categories is given in the next section.

4.2.1 Conversational methods

Conversational methods are widely used due to the natural manner in which they can be applied providing a means of verbal communication between stakeholders and analysts.
The flexibility of this method allows opinions, feelings and goals of different individuals to be uncovered. The verbally expressive demands, needs and constraints are often referred to as non-tacit requirements (Maiden and Rugg 1996). However, such methods are dependent upon the attitude and behavior of the analyst. An objective view is required whilst extracting the most useful data is very labour intensive (Christel and

King 1992, Gogeun and Linde 1993). Such techniques involve interview, focus groups, workshops and questionnaires.

4.2.2 Observational methods

Observational methods allow the basic elements of a routine to be identified whilst highlighting the needs and likely solutions to a particular design problem (Zhang 2007). These methods are particularly useful when users lack experience, are less aware of the domain demands and find requirements hard to verbalise (Zhang 2007). In contrast to conversational methods, observational methods allow tacit requirements to be collected. However, these methods are also time consuming and require the analyst to be responsive to the environment, attention to detail is needed and a structured approach is key to ensure that data is not redundant. Such techniques include social analysis, ethnographic study and protocol analysis (Nuseiben and Easterbrook 2000).

4.2.3 Analytical methods

Analytical methods are used to extract knowledge that is not directly expressed by the user, instead requirements are deduced from other information. Analytical methods can sometimes narrow the vision of the product and replication of requirements is common (Zhang 2007). It is also suggested that analytical methods are not vital to requirements elicitation, as the requirements are not captured directly from end users and customers however, they are considered an effective complementary tool. Common analytical techniques include; requirement reuse, documentation studies, laddering and repertory grid (Somerville and Sawyer 1997, Christel and King 1992, Goguen and Linde 1993 and Jiang et al 2007).

4.2.4 Synthetic methods

Synthetic methods systematically combine conversation, observation, and analysis into single methods. Users communicate in different ways to reach a common understanding of the desired product, this is often referred to as a collaborative method (Hickey et al 1999). These methods include contextual inquiry, prototyping and joint application development (JAD) and are not restricted to the user requirements stage.

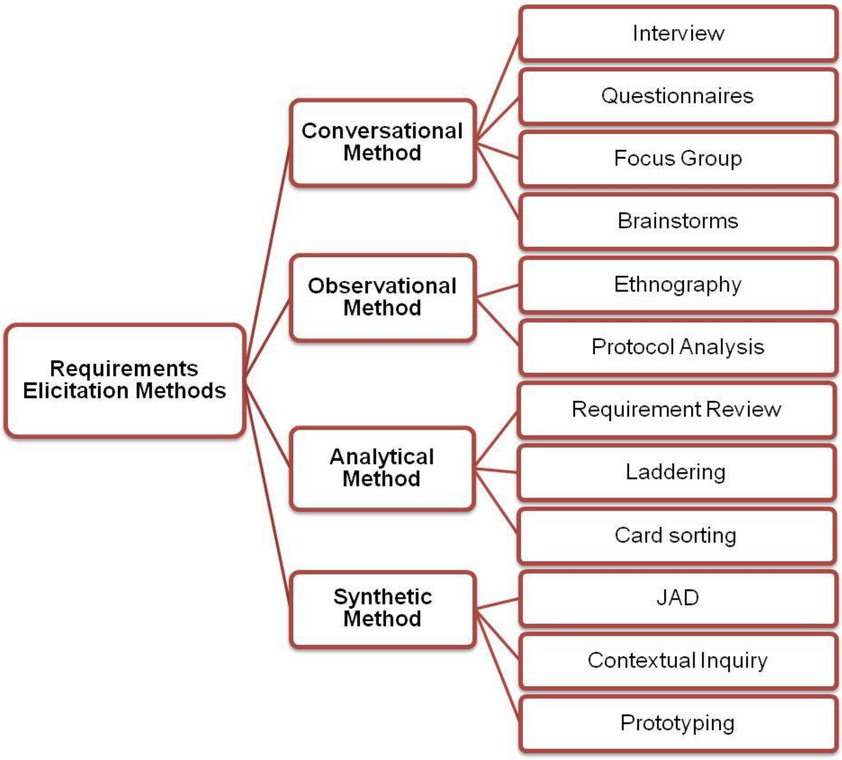


Figure 4.1 The categorisation of different requirement elicitation methods

4.3 Combining requirements elicitation methods

The relationship between knowledge acquisition, requirements elicitation and the different methods used to collect data is presented in Figure 4.2. The requirements elicitation model indicates that to acquire a range of knowledge, a combination of requirements elicitation techniques are required. In order to maximise knowledge acquisition, both observational and conversational techniques were selected as the most appropriate forms of user analysis as conducting both captures explicit, tacit, process and concept knowledge. The selected methods are circled in Figure 4.2.

Questionnaire distribution was selected as the most suitable conversational method due to the ability to access a wider user population, whilst protocol analysis was selected as the most suitable observational method. Protocol analysis accommodates task analysis which specifies the range of alternative procedures that people use based on their prior knowledge facts and procedures (Ericsson 2002). This allows the behaviour of users in their gym environment to be analysed based upon their knowledge alone.

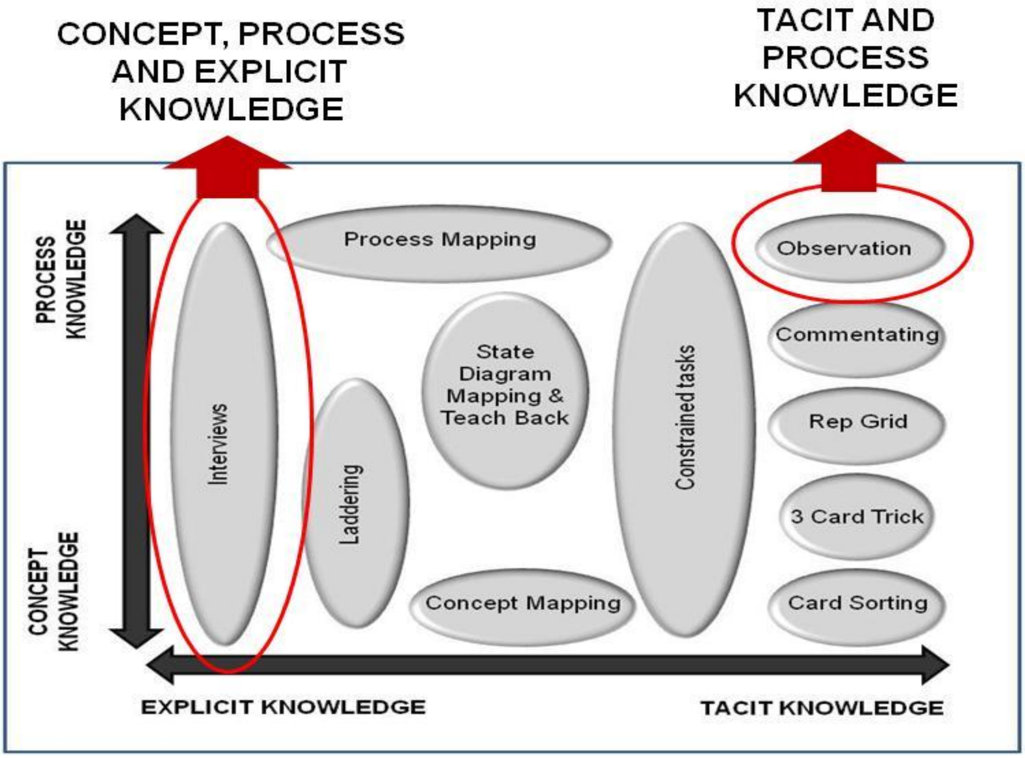


Figure 4.2 The relationship between the requirement elicitation methods and type of knowledge acquisition and identification of the most suitable methods required to ascertain explicit, tacit, concept and process knowledge.

Although the research outlined in this Chapter was focused on questionnaire data and protocol analysis, the design of the questionnaire covered several other techniques. The concept of card sorting was used to investigate user interaction (discussed in detail in Chapter 9). Synthetic methods were also used through the testing of prototypes documented in Chapters 5-7. An overview of the selected elicitation methods and accommodation of the re-iteration process proposed by the design methodology is presented in Figure 4.3. The collection and analysis of user data using these methods is documented in the remainder of this Chapter.

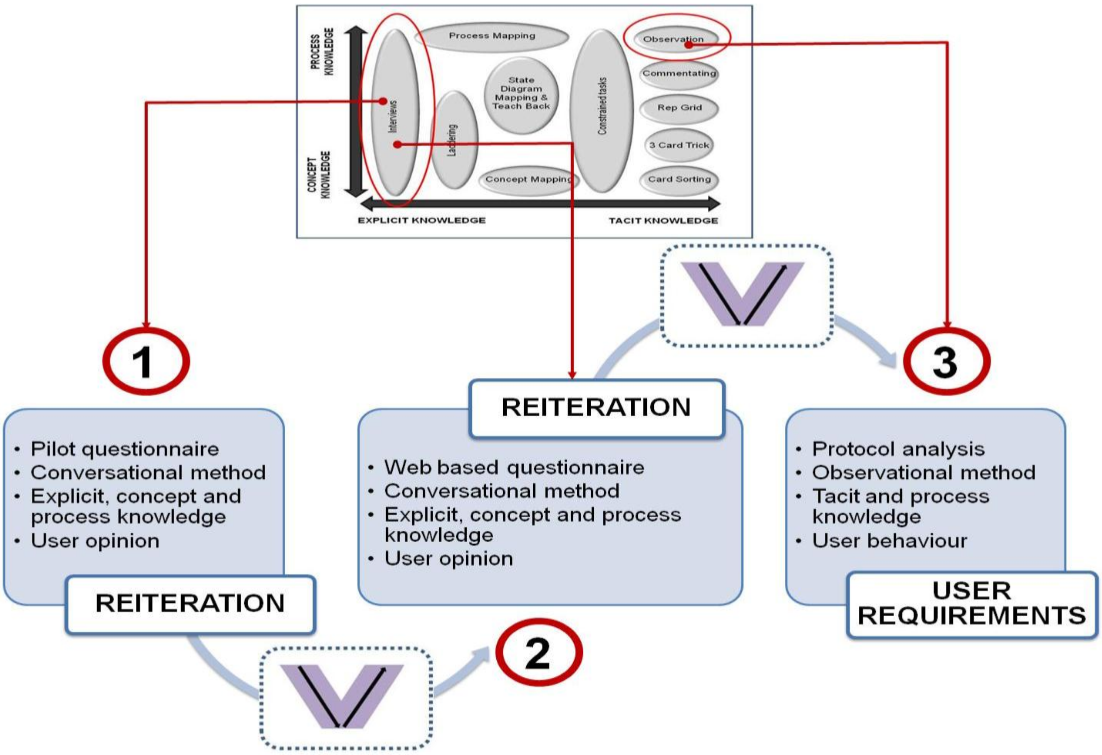


Figure 4.3 Identification of the selected requirement elicitation methods to elicit concept, process, explicit and tacit knowledge and application of the design methodology to promote user requirement elicitation.

4.4 Method 1: Pilot survey

The aim of the pilot survey was to ensure the questionnaire design was optimised. Using the design methodology principle of re-iteration and prototyping, the survey was distributed to a small sample population so flaws within the design could be identified. The basic structure of the pilot questionnaire is presented in Figure 4.4. Firstly, the experience of the user was required to determine the credibility of the data. For example, a recreational user with very limited gym experience may skew the data. By considering the user level of experience, the results can be separated into categories- the recreational, competitive, elite and experienced user. This allowed the user requirements to be considered according to the user type, a key aspect of user-centred design. The questionnaire was distributed to forty users of differing gym experience. The results are discussed in the next section.

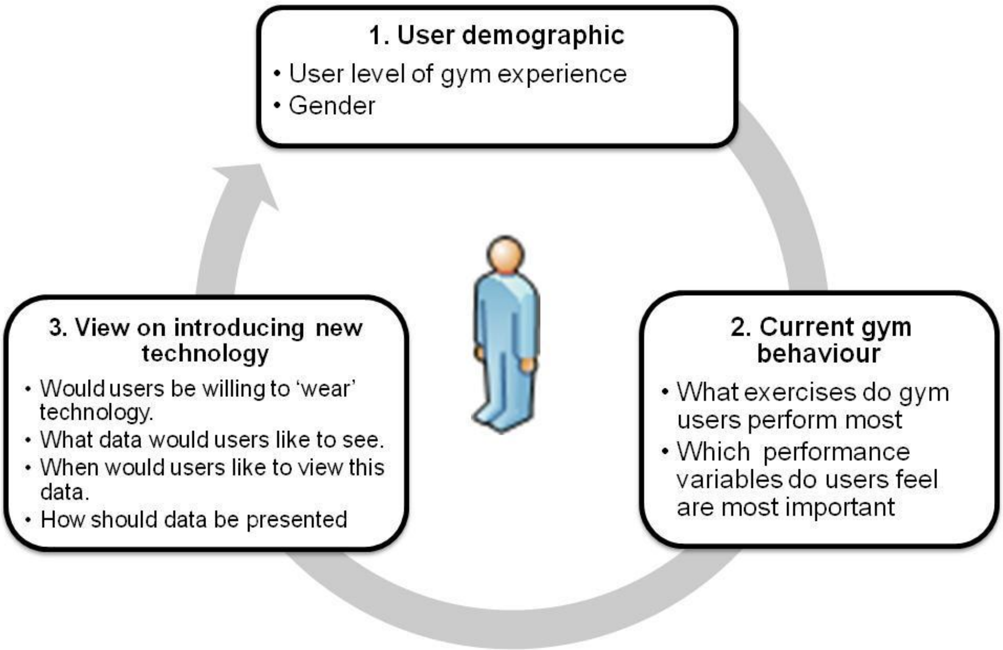


Figure 4.4 Identification of pilot survey objectives

4.4.1 Question 1-2: Defining user level of experience

An example of the pilot survey is presented in Appendix B. Initial questions focused on identifying the user gender and level of experience, the level was selected by the user as recreational, competitive, elite or experienced (coach or sports scientist). Unequal gender representation is indicated in Figure 4.5 (pie chart A), it is clear that a majority of the user feedback is male dominated. As such, comparing male and female data may identify inaccurate trends. The user level ratios illustrated in Figure 4.5 (pie chart B) indicate that a majority of the users rated themselves to be at a competitive level, this is likely as many of the questionnaires were distributed to sports teams. The pilot questionnaire revealed that a better female and male representation was required and determination of user experience needed to be modified to reduce the subjectivity of the classification. Furthermore, a user may play a sport at a competitive or elite level yet never attend the gym, therefore, rather than separating the results according to each user level, data could only be separated into recreational and experienced users. Recreational referring to those who do not coach whereas experienced being those who do coach.

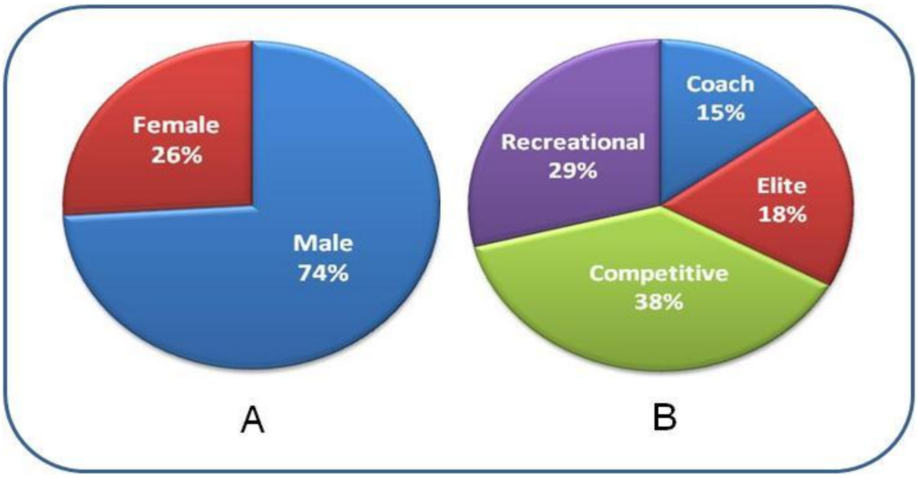


Figure 4.5 Identified flaws in pilot questionnaire; unequal gender representation and user level of experience.

4.4.2 Questions 3-4: Current gym behaviour

Question 3 required the user to select which exercises they performed in the gym from a specified list. The objective was to identify the most popular exercises and method of execution, i.e barbell, dumbbell or resistance machine. The results are presented in Figure 4.6, whilst the main conclusions are listed below:

- The exercises dominated by barbell use are the more technical lifts associated with Olympic lifting and Power lifting. Exercises such as the clean and snatch are perceived as "experienced" lifts due to the technical aspects and complexity of the movement so it is not surprising that fewer people perform these in the gym.
- The most popular exercises are those that are easier to perform and can be introduced at a beginner level. The bicep curl (an isolated exercise) proved to be the most popular exercise performed using free weights.
- The most popular compound barbell exercise is the bench press, followed closely by the squat. These exercises are performed by a broader population of varied levels due to the reduced comparative complexity to that of a clean or snatch.
- Whole body exercises are not achievable using resistance machines which are predominantly used for lower body exercises.

- The use of free weights is more popular than resistance machines, therefore it is suggested that research focus is shifted towards free weight training to determine the complexity and popularity of exercises within this domain.

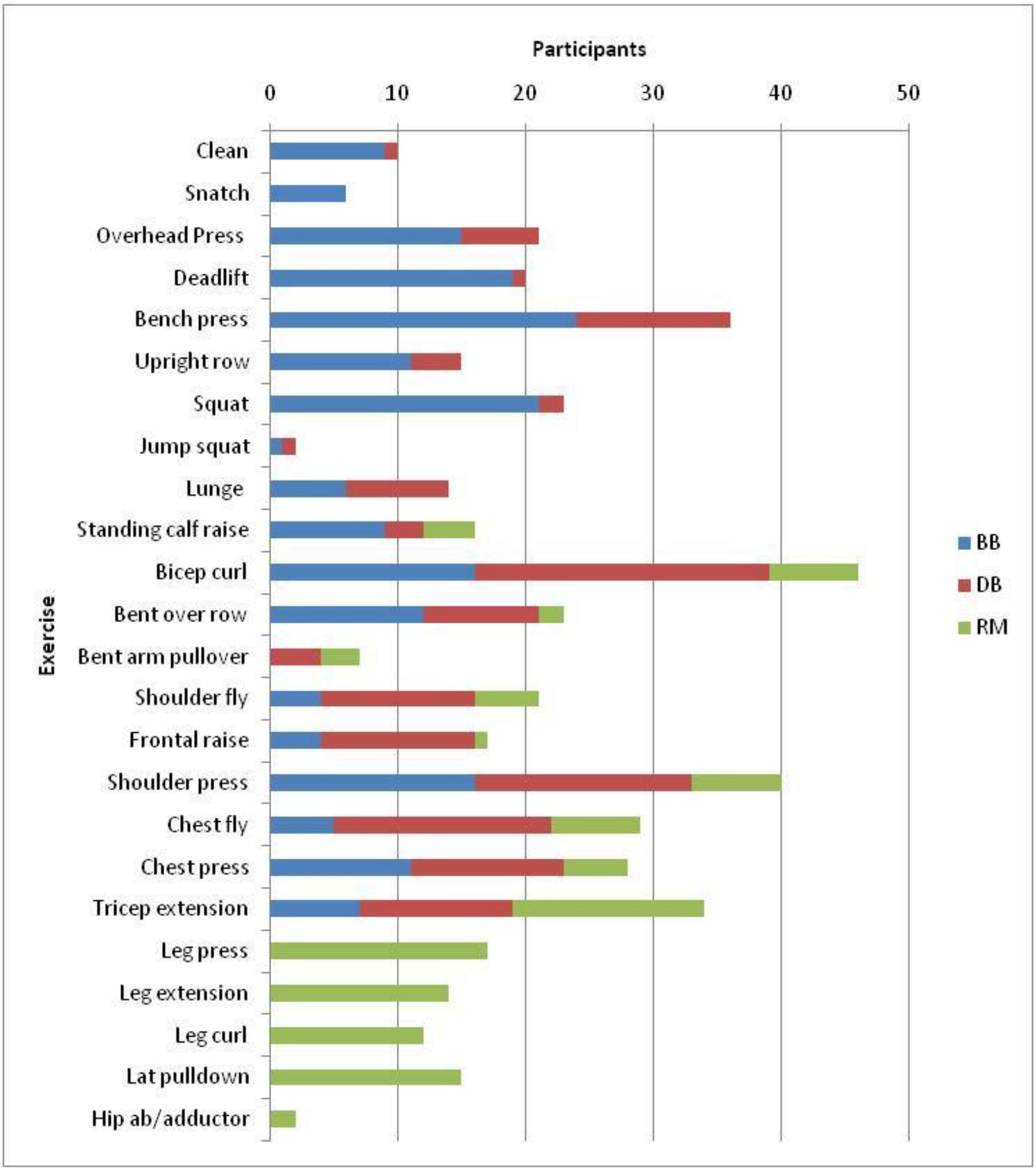


Figure 4.6 Popularity of barbell (BB), dumbbell (DB) and resistance machine (RM) based exercises performed in a gym environment

4.4.3 Question 5: Most popular performance variables

To identify the most important performance indicators, users were required to rank the variables illustrated in Figure 4.7. The variables presented to the users were selected based upon the output of the literature review presented in Chapter 3 and consideration of current gym equipment that provides performance feedback. The results are listed in Table 4.2. Parameters were ranked (from 1-7), 7 indicating the highest ranking. For example, the parameter ranked first received a score of 7, the ranking score from each user level was then added to create a total score. The total score formed the final ranking position by including the different views within each sub category of the total sample population.

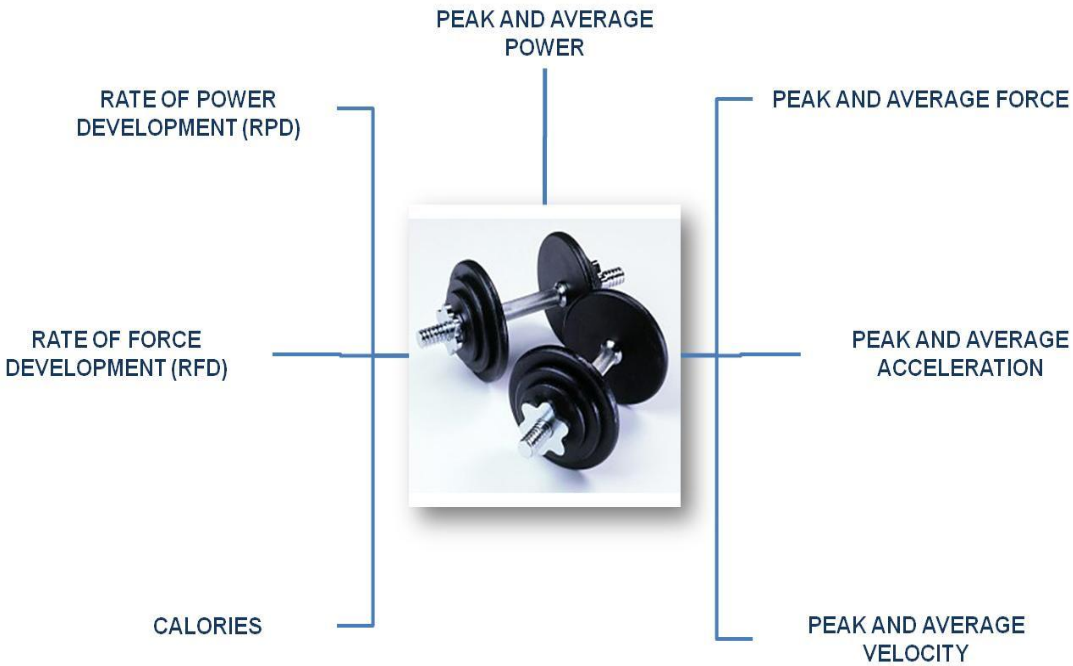


Figure 4.7 Performance variables to be ranked in order of importance by the survey participants

The overall sample population results indicated that the top variables of interest are peak and average power. This view is shared by both the experienced and recreational users. Peak and average force was ranked highly for both user types, 2nd for the recreational and 3rd for the experienced users. It is suggested that the recreational users are less aware of the term “rate of power development” and cannot appreciate its use as is reflected by the recreational ranking of RPD and RFD as the 5th and 6th most important variables. Surprisingly, peak and average velocity and work to rest ratio were low ranked parameters which suggests that data required to calculate power and force and how training programs are reliant upon effective manipulation of work to rest ratio to achieve the training goal is unknown to a majority of users. Calorie expenditure feedback is rated higher for the recreational users (3rd) than the experienced users (5th) this may be due to the familiarity with cardiovascular gym equipment which is the most common type of technology found in a gym capable of performance feedback. Cardiovascular equipment typically provides time, distance and calorie expenditure information and may influence user perception regarding what is currently available in the gym environment (Rosandich 2000).

Parameter	Recreational Score	Experienced score	Total score	Ranking
Peak and average power	7	7	14	1
Peak and average force	6	5	11	2
Peak and average velocity	4	1	5	6
Work to rest ratio	1	2	3	7
RPD	3	6	9	3
RFD	2	4	6	5
Calories burned	5	3	8	4

Table 4.1 Pilot survey ranking of the performance variables according to recreational and experienced gym users

4.4.4 Questions 6-10: Views on introducing new technology

The results from questions relating to the introduction of new wireless monitoring technology are presented in Figure 4.8. Overall the bar was identified as the preferred product location (pie chart A). However, a range of only 11% exists between bar, wrist and waist preference implying that opinion is relatively evenly spread. The next question investigated the reasoning behind location choice, whether this was due to comfort, appearance or data accuracy. The results presented Figure 4.8 indicate that the main influence is comfort (87%) (pie chart B). More significantly, the results indicate that the experienced users have a higher appreciation for the value of data collection with an equal 50% reasoning for both comfort and accuracy of data (pie chart C). This implies that coaches are more appreciative of the balance between data credibility and comfort. Preference of when to view the data identified that viewing performance data “after the set” and “during and after the set” both received a high percentage of user selection in comparison to "after the workout" or "during the set" alone (pie chart D). Finally, the majority of users preferred data to be delivered via both graphical and numerical displays (pie chart E).

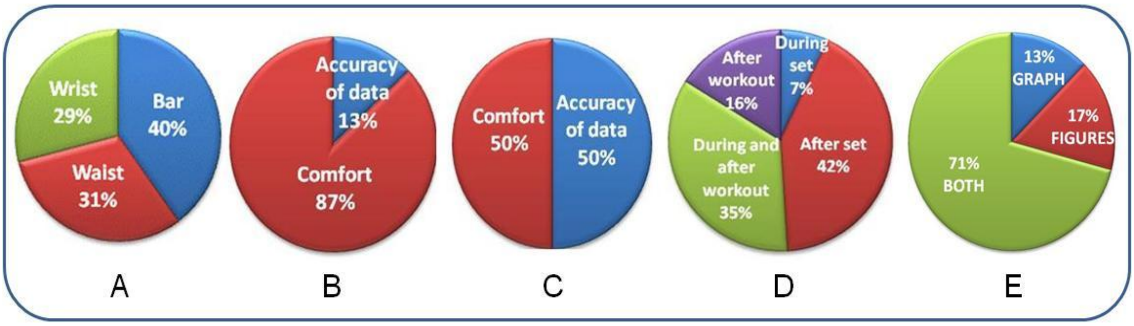


Figure 4.8 Pilot survey results regarding product location, when to view data and how to view data.

The final section of the questionnaire aimed to investigate the response of users to data presentation by presenting several example interfaces as per the examples shown in Figure 4.9. The aim was to determine whether users preferred to view a graphical display in real time, with a smaller view of a figure selected from the parameter list or a screen that only displayed numerical data in much larger font. Each interface required the user to select between reps and sets. The interface results suggest that users prefer graphical displays and to view all figures simultaneously in large font rather than cycle between values.

4.4.5 Pilot survey result summary

The pilot survey identified the following:

- The most popular compound barbell exercise is the bench press, followed closely by the squat. These exercises are able to be performed by a broader level of users due to the reduced comparative complexity to that of a clean or snatch.
- The most important variable according to all users is the average and maximum power, whilst the least important parameter is work to rest ratio.
- Most preferred product location is on the bar, but the range between wrist, bar and waist preference is only 11%.
- Users prefer to receive feedback after each set.
- Users would like functionality to choose between both graphical and numerical display.

- Users prefer to see all figures at once in large font rather than cycle between them.
- User level was classified according to the user individual subjective perception causing inaccurate distinction between each level.
- Fatigue has a major influence on performance but has not been addressed in the pilot survey.
- Whether there is a relationship between free weight exercise complexity and frequency of use needs to be investigated.
- An increase in sample population and more questions relating to user gym experience to determine whether user level affects gym behaviour and user opinion is required.
- The pilot survey enabled the identification of areas for improvement to be targeted in the second re-iteration of the questionnaire.

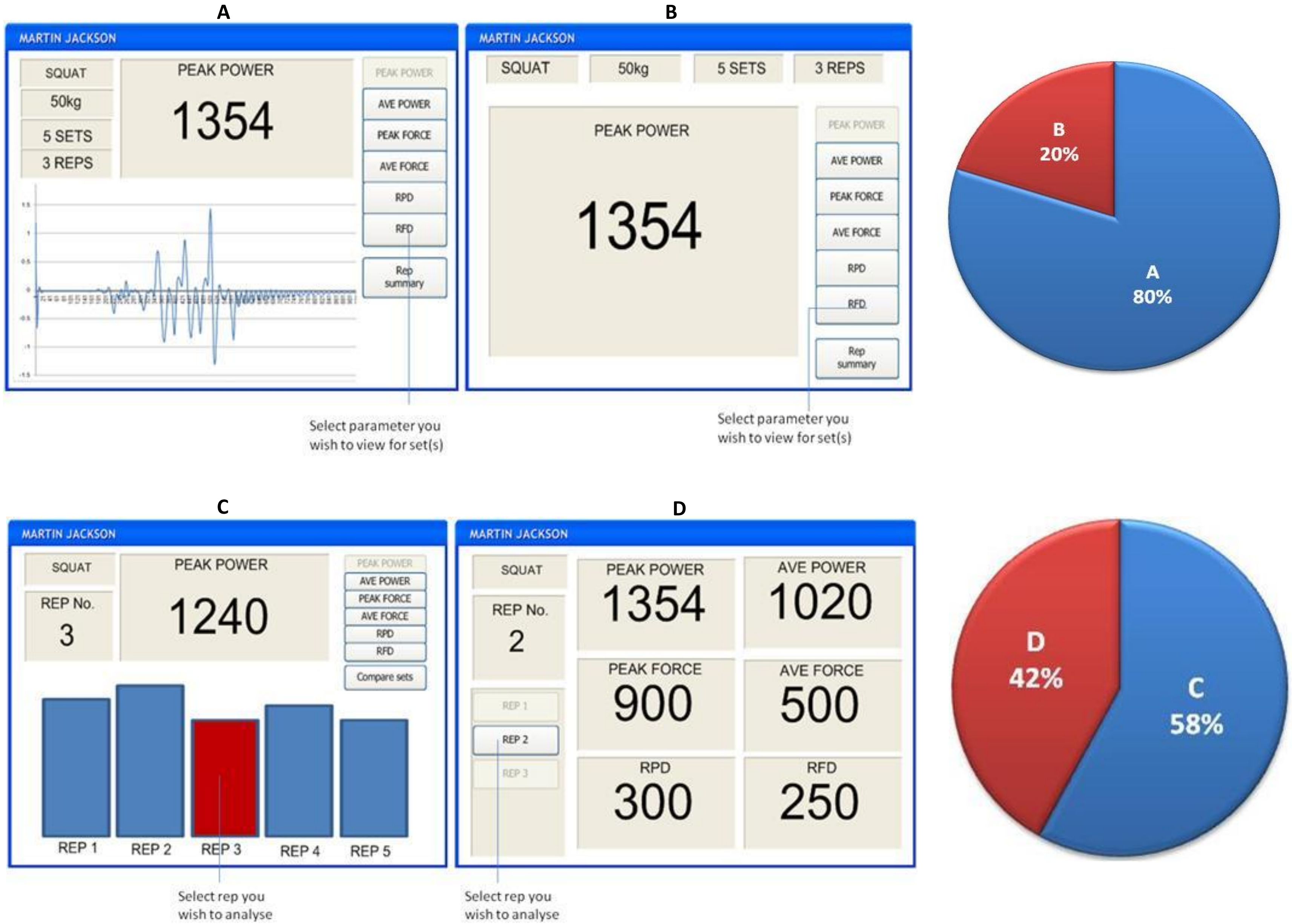


Figure 4.9 Example interfaces presented in the pilot survey and corresponding user preference results that suggest users prefer both graphical and numerical display rather than graphical or numerical display in isolation

4.5 Method 2: Questionnaire

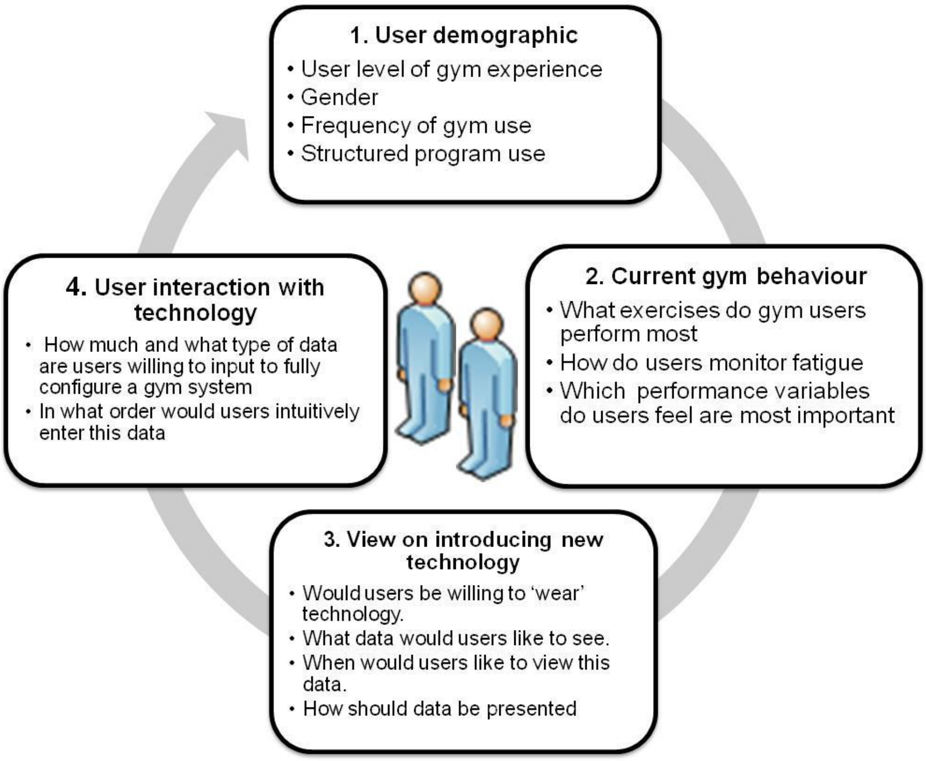


Figure 4.10 Identification a re-iterated web based questionnaire

The main questionnaire was developed through a re-iterative process designed to optimise the quality of the feedback obtained. A web based questionnaire was chosen to increase user access and question variation. A review of the revised objectives with the additional component of user interaction is presented in Figure 4.10. Due to the ability to create more interactive questions, performance feedback software was simulated to investigate user interaction with technology. The user was required to identify how they would achieve a particular task such as "create a new profile", by selecting from a predefined list the order and number of actions they would complete to achieve this task. The aim of the new component was to gain feedback on user interaction and software navigation i.e targeting Human-Machine Interaction (HMI) and supplementing feedback on data presentation. Furthermore, to improve understanding of current gym behaviour, exercise popularity was adapted to focus upon complexity and frequency of free weight use. User opinion regarding onset of fatigue was also investigated as this was neglected in the written questionnaire.

Statistical analysis was conducted using the significance level as the criterion for rejecting the null hypothesis. The significance level can be used for numerous statistical parametric and non-parametric tests to determine the significance of the results. The difference between the results of the experiment and the null hypothesis is first determined. Assuming the null hypothesis is true, the probability of a difference is computed and this probability is compared to the significance level. If the probability is less than or equal to the significance level, then the null hypothesis is rejected and the outcome is said to be statistically significant. Most commonly the 0.05 level (5% level) or the 0.01 level (1% level) is used to determine whether the null hypothesis is rejected. The lower the significance level, the more the data must diverge from the null hypothesis to be significant (Brase 2011). Correlation coefficients were calculated to determine relationships between ranked variables and user level of experience. As the data was not continuous and ranking methods were used, the non-parametric equivalent of the Pearson's correlation coefficient was applied (Spearman's correlation coefficient) (De Levie 2004).

Closed questions were predominantly used rather than open ended questions. A closed question can be answered with a single word or phrase, whilst open ended questions require longer answers. Closed questions were most suitable for ranking variables and obtaining facts. Given the nature of the web based questionnaire, closed questions also reduced the risk of the respondents skipping questions or rushing the answers. Although open ended questions force the respondent to reflect and give them more flexibility in their response, the aim was to collect focused and factual data (Oppenheim 2000). The questionnaire allowed factual data to be collected, however, using this method alone increases the risk of missing vital data regarding user behaviour. Identifying user requirements cannot rely upon questionnaire data alone, observational techniques would provide additional data that cannot be predicted.

4.5.1. Questions 1-4: Defining user experience level

To ensure the normal distribution of data a sample size >30 is required. The larger the sample size, the higher the probability the data will be normally distributed and a better representation of the population will be achieved (De Levie 2004). Therefore, the sample user population was increased from 40 to 110 users providing a better representation of the overall population. Using a web based method allowed the data to be analysed in a more structured manner. A method of cross filtering facilitated by the web based software, allowed certain rules to be applied using “and/or” logic to filter user feedback. This method enabled the effect of both user level and gender to be investigated. In contrast to the written questionnaire, user level was determined using numerous questions rather than subjective user opinion alone. This was achieved by considering frequency of gym use, whether a structured program was followed and finally what level they considered themselves to be at. This reduced the subjectivity of perceived user level. Combining the answers to each of these questions allowed the data to be filtered using the following and/or logic:

NOVICE: Recreational AND do not follow a structured program OR never visit the gym.

INTERMEDIATE: Recreational OR competitive, follow a structured program AND visit the gym at least twice a week

EXPERIENCED: Coach OR elite, follow a structured program AND visit the gym at least twice a week.

The results are presented in Figure 4.11. Gender representation is more equal than the written questionnaire allowing differences in user opinion based on gender to be investigated (Figure 4.11, pie chart A). More than half the sample population do not follow a structured training program (Figure 4.11, pie chart B) whilst, 75% of these users visit the gym at least twice a week. This alone highlights a need to encourage a structured approach to training. Finally, the user distinction indicated that a majority of the population were recreational users (Figure 4,11, pie chart C). To determine whether user level also affected current behaviour in the gym environment, the same questions relating to the most important variables, product location and method of viewing data were asked.

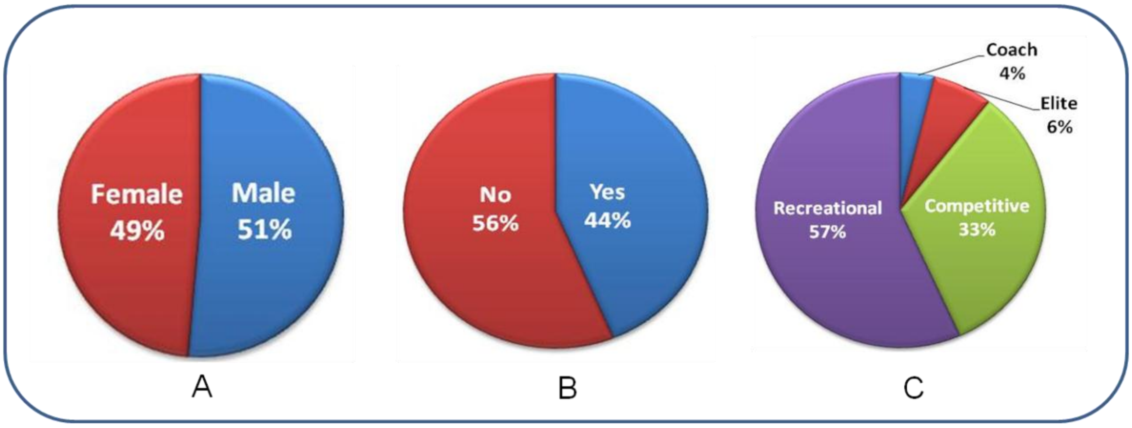


Figure 4.11 Questionnaire results regarding gender balance (A), whether users follow structured programs (B) and user experience level (C).

4.5.2 Questions 5: Exercise complexity and frequency of use

Exercise popularity was investigated using the written questionnaire, the results indicated that free weight use was most popular. In order to investigate fully free weight use, Olympic and Powerlifting exercises were analysed. There is a wide variety of compound barbell exercises, these variations and developmental lifts stem from the Olympic and Powerlifts. The exercises selected to be evaluated by users and the reliance upon the ability to perform the developmental lift are presented in Figure 4.12. Coaches often use variations and developmental techniques which provide the building blocks for complete Olympic lift execution, therefore, each of these exercises were presented to the user to determine if they could distinguish between complexity and whether this influenced the frequency of use.

Each subject was required to rate each exercise on a scale from 1-10 according to complexity (1 corresponding to extremely easy and 10 being very difficult) and frequency of use (1 being never and 10 being every session). The average complexity value and frequency value was calculated for each exercise, results are presented in Figure 4.13. The negative relationship indicates that frequency of use decreases as complexity of the exercise increases.

The average complexity and frequency of use score for each exercise and consideration of the relationship between developmental, variations, Olympic and Power lifts is represented by the diagram presented in Figure 4.14. This diagram utilises the graphical results in Figure 4.13. The arrows are used to indicate which lifts are reliant upon the ability to perform another lift. The origin of the arrow denotes a lift that is required to achieve the connected exercise, ultimately highlighting the dependency between lifts. The Power lifts are considered to be easier than the Olympic lifts, the arrows highlight the reliance of the Olympic lifts upon the ability to perform the simpler lifts. To identify the most popular exercises, a “reliance” value was determined based on how many other lifts relied upon the ability to perform that particular exercise. This was determined by the number of arrows originating from each lift and inserting to another. The results are presented in Figure 4.14. The results indicate that most exercises rely upon the ability to perform a squat, whilst the deadlift also plays an important role in executing the more complex lifts.

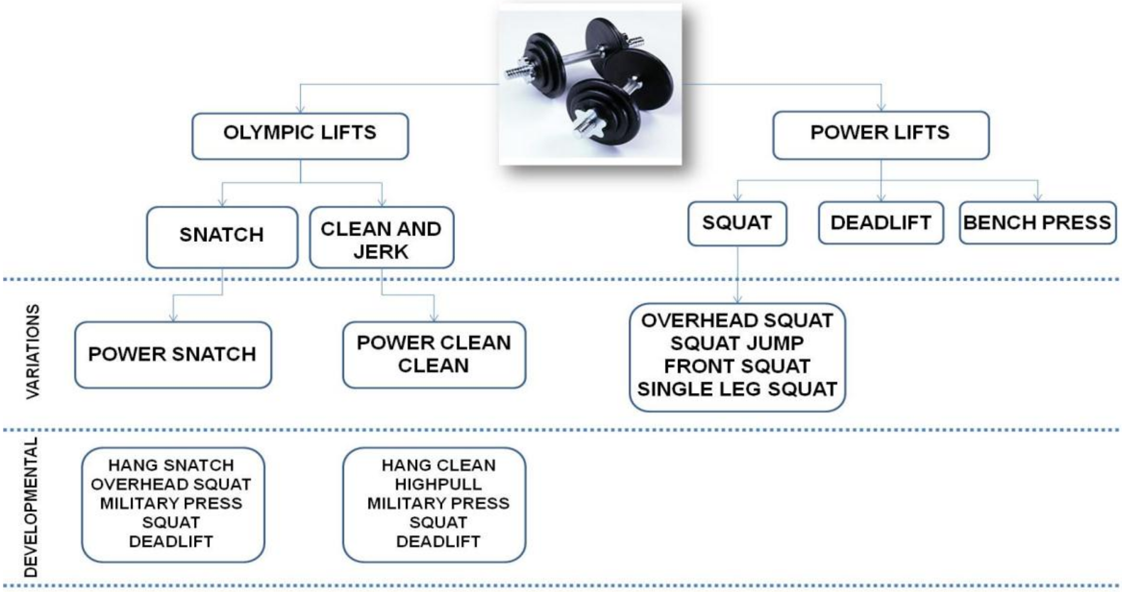


Figure 4.12 List of exercises free weight exercises chosen to be ranked in terms of complexity and frequency of use.

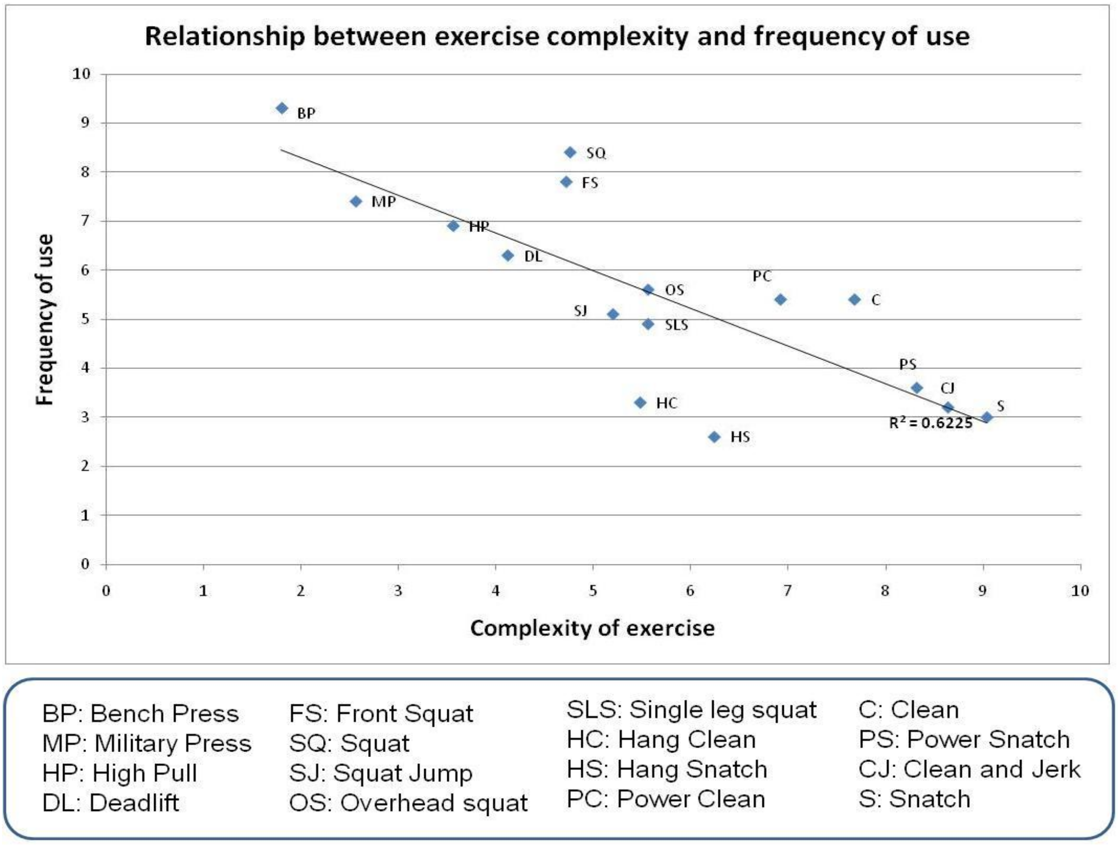


Figure 4.13 Relationship between exercise complexity and frequency of use using the ranking of the exercises listed in Figure 4.10.

Exercise	Bench press	Military press	Squat	Front squat	High pull	Deadlift	Squat jump	Overhead squat	Single leg squat	Power clean	Clean	Hang clean	Power snatch	Hang snatch	Clean and jerk	Snatch
Reliance value	0	2	7	5	3	4	1	1	0	1	1	2	1	1	0	0

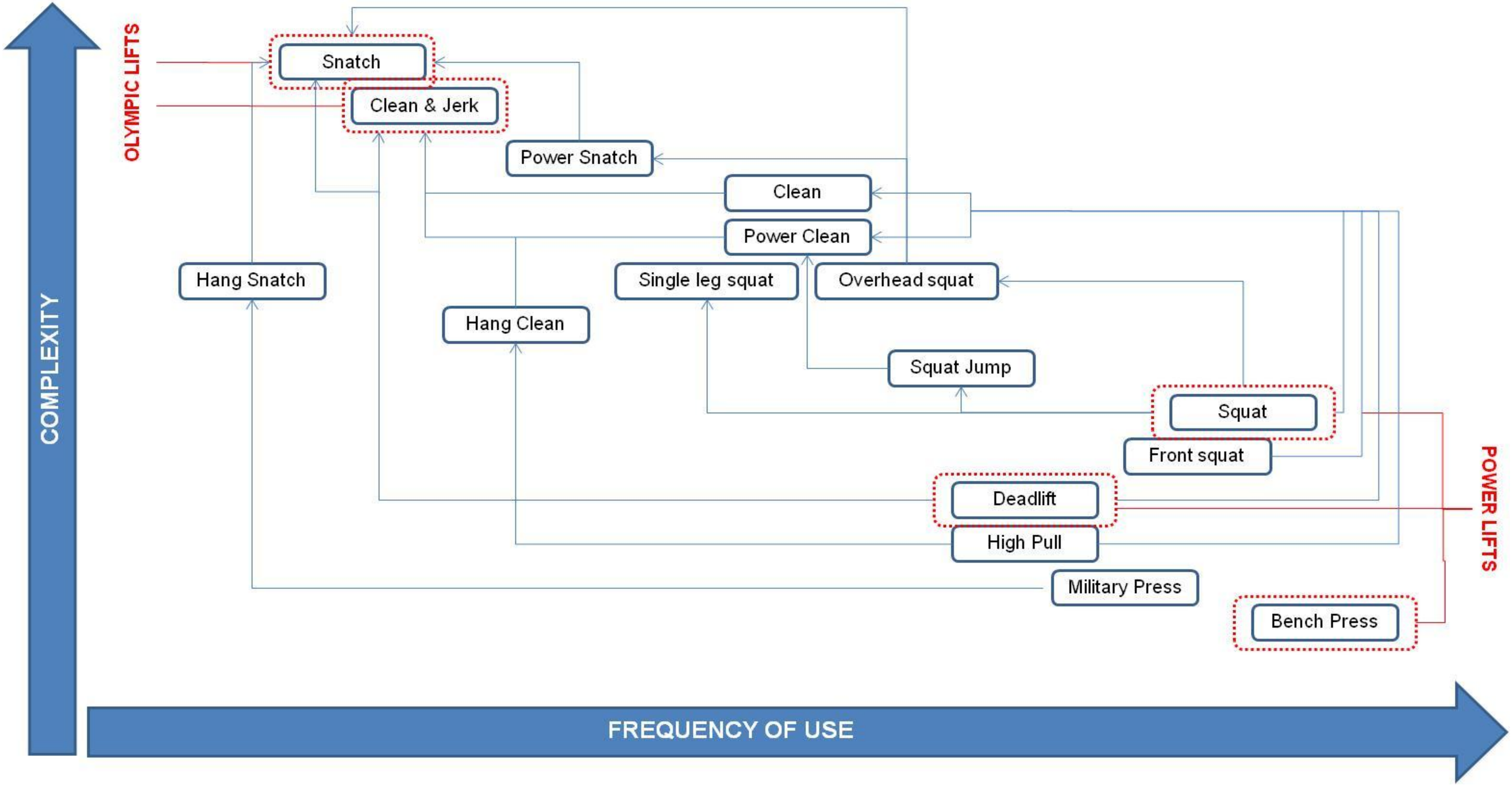


Figure 4.14 Calculation of a reliance value using the number of arrows entering and leaving each exercise to determine the relationship; the higher the number of arrows leaving the exercise the higher the reliance value.

4.5.3 Question 6: Fatigue indicators

To identify how users currently gauge onset of fatigue, the same ranking method as the performance variable question was proposed. The categories presented to the users are identified in Figure 4.15, once again, these were selected based upon relevant literature reviewed in Chapter 3. The results are listed in Table 4.2. The correlation coefficients were calculated to determine the level of agreement between gender, user level and ranking of fatigue indicators. The results are presented in Table 4.3.

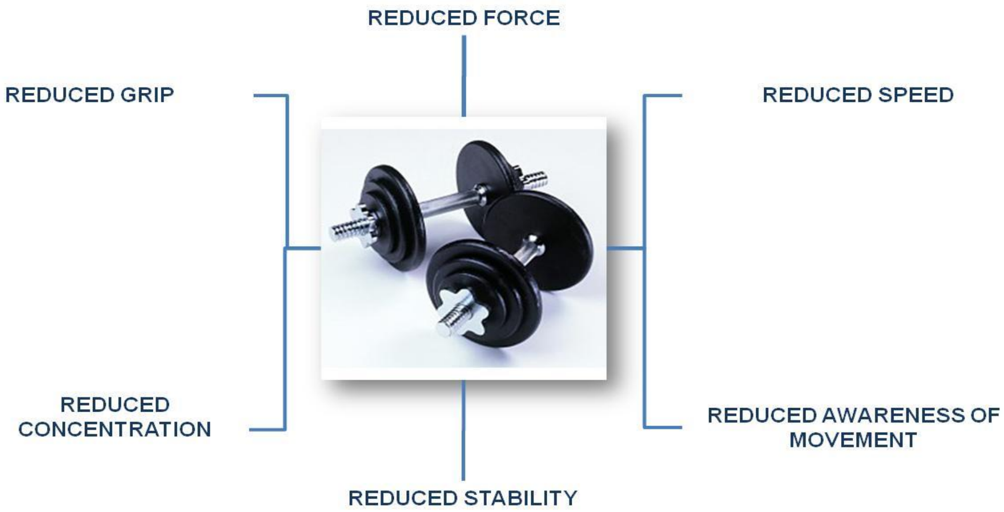


Figure 4.15 Selection of fatigue indicators using the knowledge acquired in Chapter 3.

Current fatigue indicator	Female score	Male Score	Novice score	Intermediate score	Experienced score	Total score	Overall Rank
Reduced force	6	6	6	6	6	30	**1**
Reduced speed	5	5	5	5	5	25	**2**
Reduced awareness of movement	3	4	3	3	4	17	**4**
Reduced stability	4	3	4	4	3	18	**3**
Reduced grip	1	2	1	2	2	8	**5**
Reduced concentration	2	1	2	1	1	7	**6**

Table 4.2 Ranking of fatigue indicators according to gender, experience level and total population

Correlations

		Female	Male	Novice	Intermediate	Experienced
Female	Spearman Correlation	1	.886*	1.000**	.943**	.886*
	Sig. (2-tailed)		.019	.000	.005	.019
	N	6	6	6	6	6
Male	Spearman Correlation	.886*	1	.886*	.943**	1.000**
	Sig. (2-tailed)	.019		.019	.005	.000
	N	6	6	6	6	6
Novice	Spearman Correlation	1.000**	.886*	1	.943**	.886*
	Sig. (2-tailed)	.000	.019		.005	.019
	N	6	6	6	6	6
Intermediate	Spearman Correlation	.943**	.943**	.943**	1	.943**
	Sig. (2-tailed)	.005	.005	.005		.005
	N	6	6	6	6	6
Experienced	Spearman Correlation	.886*	1.000**	.886*	.943**	1
	Sig. (2-tailed)	.019	.000	.019	.005	
	N	6	6	6	6	6

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.3 Spearman's correlation coefficient values indicating high agreement between the female and novice and male and experienced users using the ranking of fatigue indicators.

Overall, there is high correlation between all the user groups with all groups exhibiting a significant level of correlation at the 0.05 and 0.01 level (Baumgartner and Chung 2001). The novice and female values are less correlated with other user groups (female and novice are significantly correlated at the 0.01 level) it can be assumed that most novice users are female. Highest correlation is found between the experienced and male results, with least correlation between experienced and female or novice results. This supports further the hypothesis that a higher majority of novices are female and more experienced gym users are male. It is agreed by all users that reduction in force production is rated as the most common fatigue indicator, whilst reduced speed is the second most important. Detecting reduction in speed and force may be required before a session rather simply during, as it may provide information regarding a user's "readiness to perform". According to Thibadeau (2007) this would be a very useful tool and a fundamental aspect of performance analysis. Therefore, providing quantitative feedback that may indicate fatigue during a session and between different sessions whilst quantifying a user's readiness to perform will form one of the main user requirements.

4.5.4 Question 7: Performance variables

Users were required to select from the same seven parameters in the written questionnaire. Each parameter was then given a score according to the rank, the higher the rank the higher the score (1-7). The order of the parameters was determined by considering the cumulative number of users to select the rank number. The gradient of the each line depicted in Figure 4.16 was used to identify the point at which most users were in agreement, the steeper the line, the higher the user agreement. This overcomes instances where two parameters or more exhibit the same ranking number, the gradient of the line highlights where users have shown more agreement. For example, 3 parameters have been ranked 5th in the novice plot by the same number of users. The RFD line gradient from 4th to 5th is steeper than that of velocity and work to rest ratio, indicating that more users agree upon that ranking position being suited to RFD.

Both intermediate and experienced users agree that “average and maximum power” are the most important performance variables, whilst novices feel it is still of high importance, resulting in 2nd place. Both the novice and experienced results show a clearer distinction between each rank, the steeper gradients of each line indicate higher agreement between users, alternatively the intermediate results exhibit less steep gradients and higher correlation. This would imply that intermediate users exhibit less agreement, the lower cumulative percentage values indicate that opinion at each rank was broadly spread.

Rankings from 2nd to 5th indicate a less conclusive and agreement between users due to the lower percentage of population. Such low results imply that other parameters also shared a similar proportion of the vote. Each of the cross filtered group results are valuable, therefore, the ranking results have been combined to discover the overall rankings. A summary of the ranked results according to each cross filtered group and resultant correlation coefficients are listed in Tables 4.4 and 4.5.

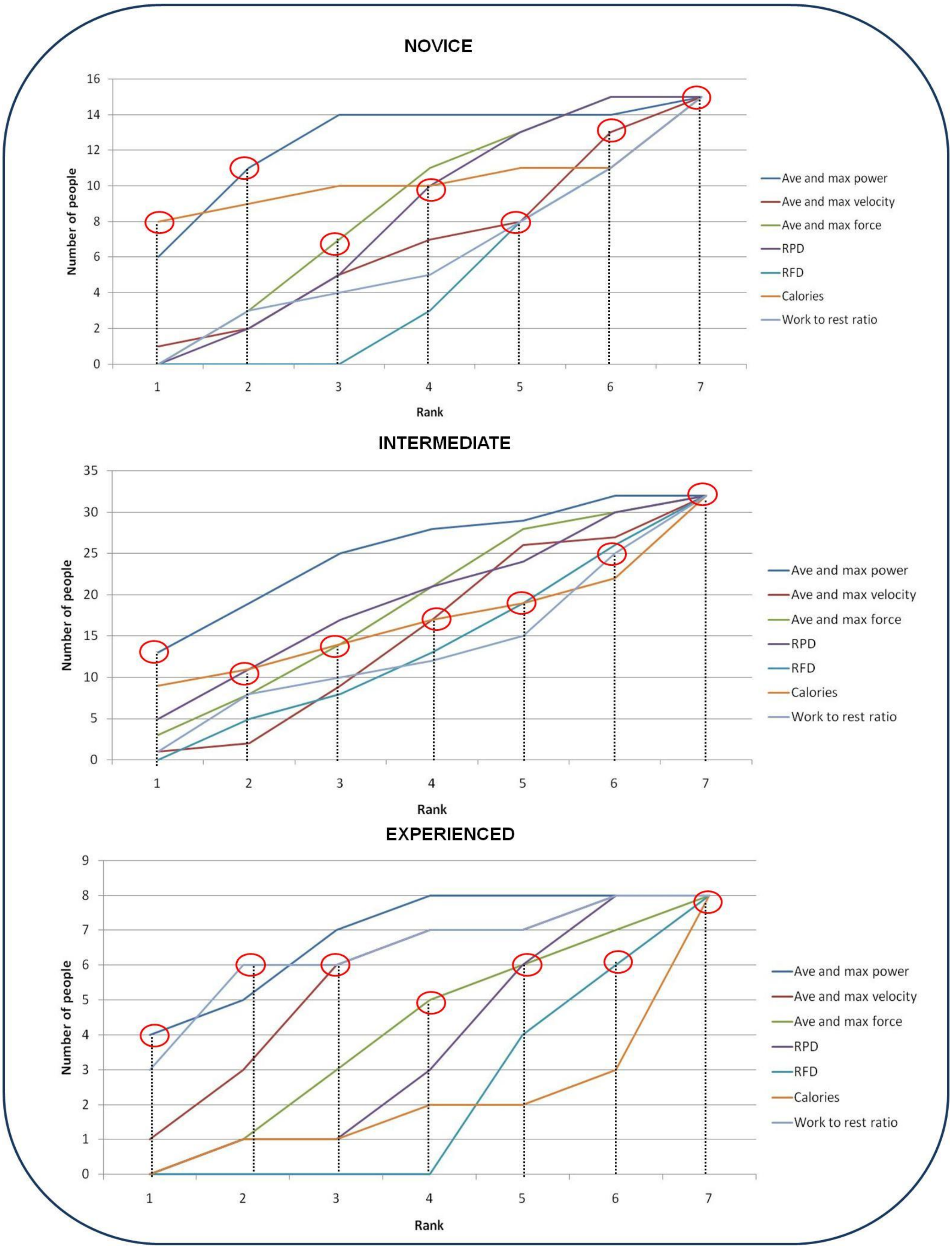


Figure 4.16 Ranking of performance variables considering the agreement between users indicated by the steepness of the line rather than using cumulative value alone.

Parameter	Female score	Male score	Novice score	Intermediate Score	Experienced score	Total score	Overall Rank
Ave and max power	6	7	6	7	7	33	**1**
Ave and max velocity	3	5	2	4	5	19	**3**
Ave and max force	4	6	5	5	4	24	**2**
RPD	2	3	4	6	3	18	**4**
RFD	1	4	3	3	2	13	**7**
Calories	7	1	7	1	1	17	**5**
Work to rest ratio	5	2	1	2	6	16	**6**

Table 4.4 Ranking of performance variables according to gender, experience level and total population

Correlations

		Female	Male	Novice	Intermediate	Experienced
Female	Spearman Correlation	1	-.143	.536	-.214	.214
	Sig. (2-tailed)		.760	.215	.645	.645
	N	7	7	7	7	7
Male	Spearman Correlation	-.143	1	.107	.786*	.571
	Sig. (2-tailed)	.760		.819	.036	.180
	N	7	7	7	7	7
Novice	Spearman Correlation	.536	.107	1	.179	-.321
	Sig. (2-tailed)	.215	.819		.702	.482
	N	7	7	7	7	7
Intermediate	Spearman Correlation	-.214	.786*	.179	1	.500
	Sig. (2-tailed)	.645	.036	.702		.253
	N	7	7	7	7	7
Experienced	Spearman Correlation	.214	.571	-.321	.500	1
	Sig. (2-tailed)	.645	.180	.482	.253	
	N	7	7	7	7	7

*. Correlation is significant at the 0.05 level (2-tailed).

Table 4.5 Spearman's correlation coefficient values indicating highest agreement between the male and intermediate users using the ranking of performance variables.

Little correlation and difference in user type opinion is indicated by the results shown in Table 4.5. A significant level of correlation is only apparent between the male and intermediate results. This implies that gender and user level do influence which parameters are considered to be most important. Once again, work to rest ratio is considered a parameter of little importance regardless of user type. As mentioned previously, this is surprising as work to rest ratio is one of the training acute variables. As mentioned in Chapter 3, the manipulation of the acute variables (i.e sets, reps, load and intensity) control whether the goal of training is endurance, hypertrophy, strength or power. Intensity is controlled by the work to rest ratio, therefore, it should be considered a fundamental part of a training program but may only be known to more experienced users. This is reflected in Table 4.6 in which the experienced users rank this parameter to be the second most important variable. As such, it is suggested that although the overall ranking score places the work to ratio in penultimate position, it should be of a higher rank to reflect the more experienced views. Such differences in opinion will not be reflected should the original data be used, as the sample population is dominated by recreational and competitive response. Therefore combining the cross filtered ranking scores to determine the ranking of each parameter provides a more accurate representation of the data. The effect of cross filtering and ranking the data according to gender and user experience in comparison to the original results is demonstrated in Figure 4.17.

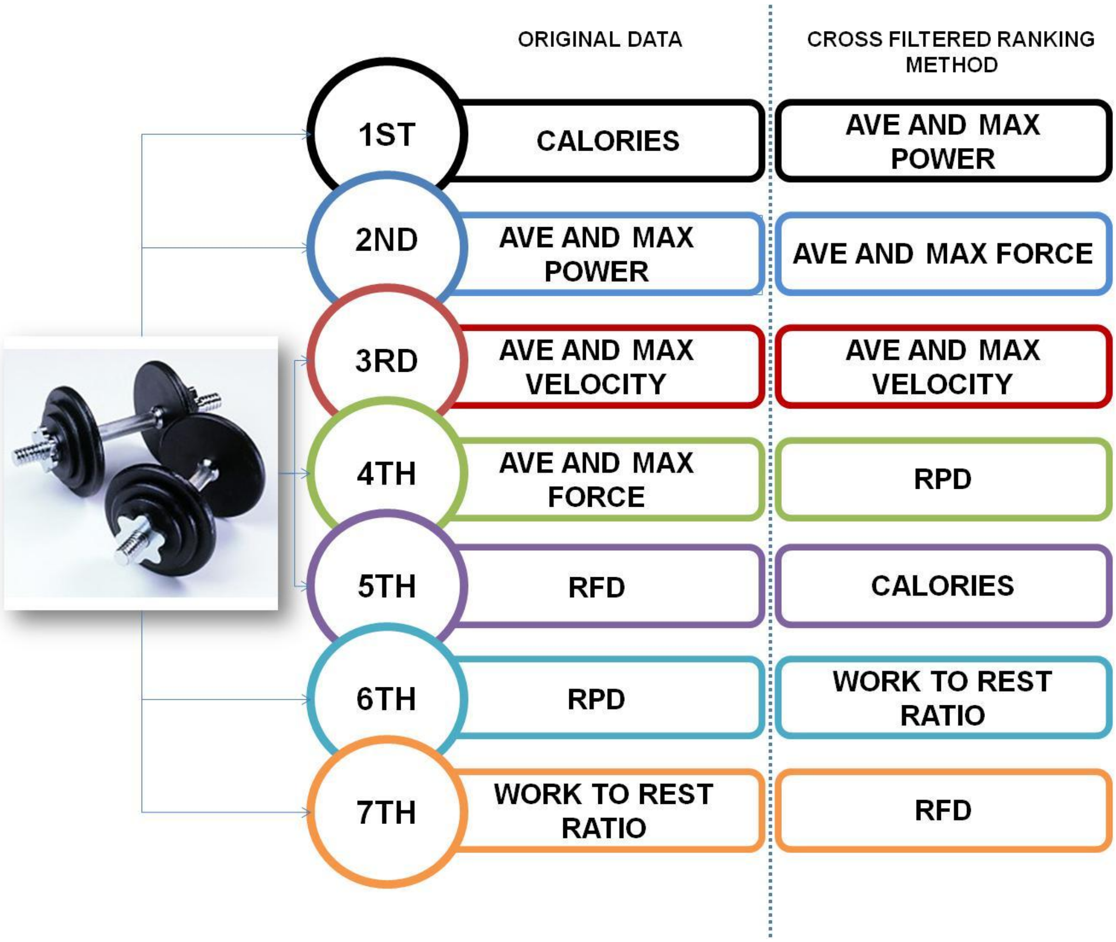


Figure 4.17 Ranking of performance variable using the cross filtering method to apply more weighting to the experienced and elite views.

4.5.5 Question 8-10: Views on introducing new technology

The same questions targeted by the pilot survey to investigate the introduction of new technology were revisited using the web based method. The results for preferred product location, when to view results and viewing preference are presented in Figure 4.18. The results exhibit agreement with the pilot survey trends. The preferred product location was the bar (Figure 4.18, pie chart A) and the functionality to view both graphical and numerical feedback both during and after each set was most preferred (Figure 4.18, pie chart B and C). The final component regarding user interaction provided an abundance of data that related to Human-Machine Interaction, as result this data is discussed separately in Chapter 8 which investigates software development.

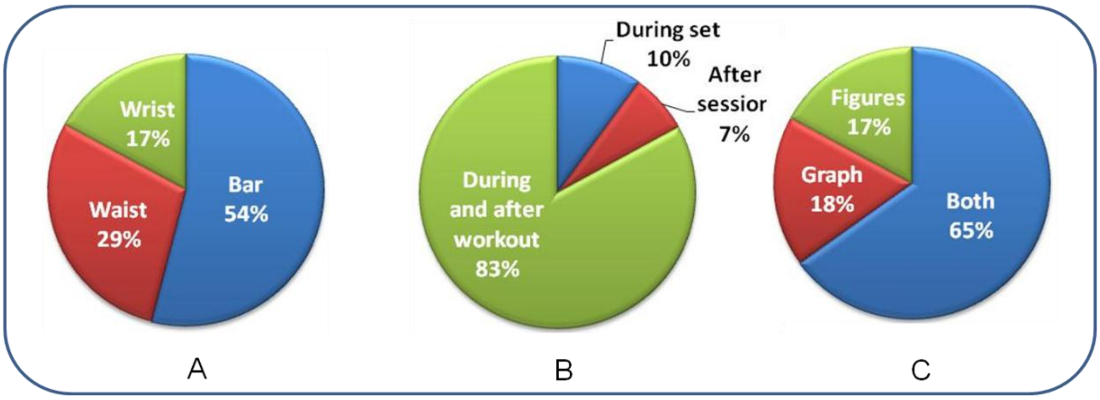


Figure 4.18 Questionnaire results regarding product location (A), when to view data (B) and how to view data (C).

4.5.6 Questionnaire results summary

The combination of pilot survey and web based results are listed in Table 4.6 and Figure 4.19. The overall results reflect agreement regarding the most important parameters but also lack of agreement regarding what is least important. Throughout the analysis, power, force and velocity have remained highly rated parameters, whilst, calorie expenditure, RFD and work to rest ratio have been inconsistently placed. The ranking method aimed to reduce the impact of less experienced users and counteract inconsistency by separating the results according to user type. However, users may not behave as they perceive themselves to, therefore, the final stage in defining the user requirements aimed to use an observational method in a gym environment to investigate whether users follow structured programs that effectively use the acute variables to target endurance, hypertrophy, strength or power and which exercises are most commonly performed. Conducting this research in addition to the previous data collection investigated whether users perform in the same way that they think they do, reducing the influence of users who may say what the analyst wants to hear, whilst also distinguishing between RFD, calories and work to rest ratio.

PARAMETER	PILOT	QUESTIONNAIRE	Total score	Overall rank
Ave and max power	7	7	**14**	**1**
Ave and max velocity	6	5	**11**	**2**
Ave and max force	2	6	**8**	**3**
RPD	1	4	**5**	**4**
RFD	5	1	**6**	**5**
Calories	3	3	**6**	**5**
Work to rest ratio	4	2	**6**	**5**

Table 4.6 Ranking of performance variables according to the pilot survey, questionnaire and resultant overall ranking.

4.6 Method 3: Protocol analysis (verbal and non verbal)

Figure 4.19 Combined pilot survey and questionnaire ranking of performance variables.

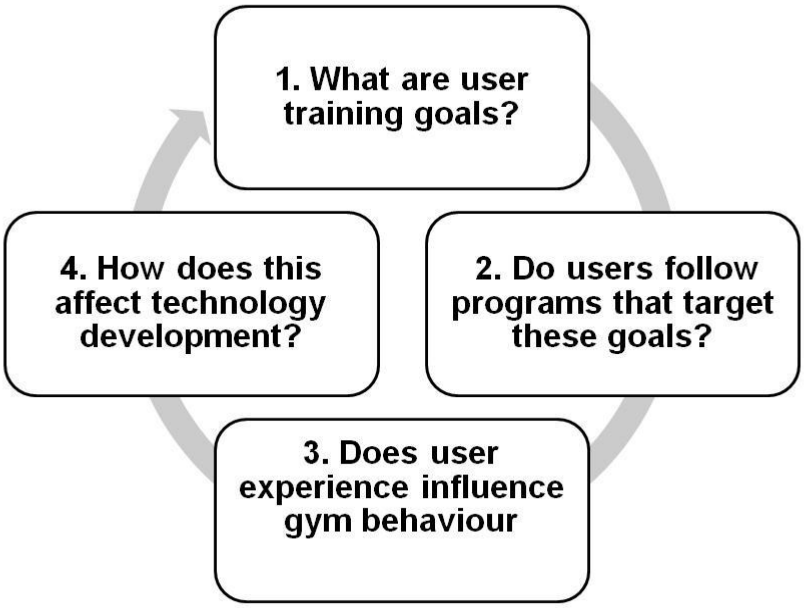


Figure 4.20 Identification of protocol analysis objectives

The main objective of this case study was to determine whether users apply the appropriate structure to their program to achieve their specified training goal using an observational requirements elicitation method known as protocol analysis. As stated previously, protocol analysis accommodates task analysis which specifies the range of alternative procedures that people use based on their prior knowledge facts and procedures (Ericsson 2002). A total of 26 subjects of differing user levels were observed in the gym environment. Subjects were asked to conduct their session as normal, whilst narrating their activity when possible. The subjects were not informed of the study objective so that they would not alter their behaviour to suit the analyst. Each subject was asked to identify their training goal at the start of their session from the following four categories:

1. Muscular endurance
2. Muscle gain (hypertrophy)
3. Muscular strength
4. Power

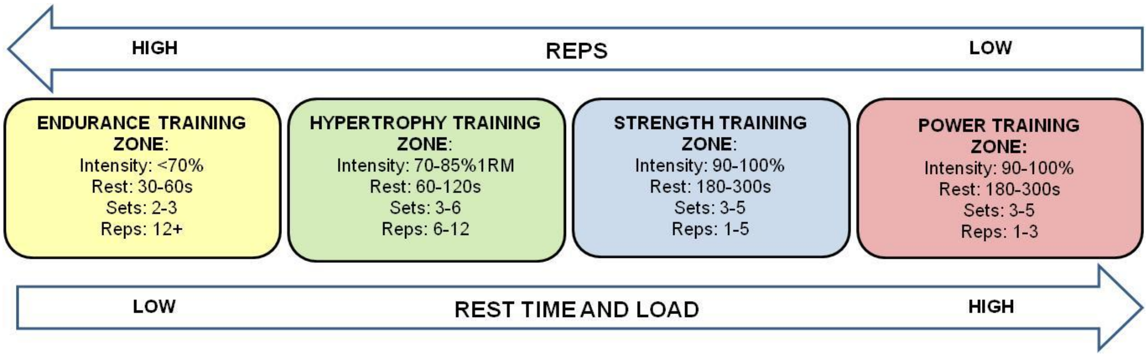
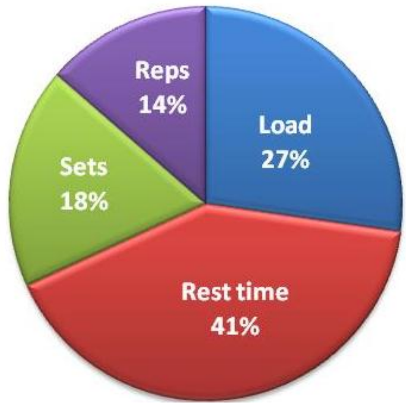


Figure 4.21 The acute variables required to target the four training systems; endurance, hypertrophy, strength and power

Targeting each training goal is dependent on manipulation of the principles of training: Frequency, Intensity, Time and Type. Intensity is controlled by the number of sets reps, load and work to rest ratio. The relationship between the training goals and acute variables was first addressed in Chapter 3. For reference, the strength-endurance continuum is presented in Figure 4.21. The load, sets, reps and rest time were recorded for each subject throughout the session, this was then compared to the sets, reps, load and rest time that should be applied based upon their specified training goal. The results are presented in the following section.

4.6.1. Protocol analysis results

The percentage of users training for either, endurance, hypertrophy, strength or power is presented in Table 4.7. A majority of users train to increase muscle size (hypertrophy), followed by strength, power and finally endurance. To determine whether users followed a program that correctly adapted the acute variables to the specified training goal, load, rest time, sets and reps completed were compared to the specified guidelines for that particular training goal. According to Table 4.7, 41% of ineffective training results from inappropriate application of rest time, with the highest amount of ineffective training occurring in the hypertrophy zone. The number of users who failed to adhere to their specified training zone and whether this was due to inappropriate load, rest time, sets or reps is also presented in Table 4.7.

TRAINING GOAL	MOST COMMON MISUSE OF ACUTE VARIABLES
	

Number of users				
	Inappropriate load	**Inappropriate rest time**	**Inappropriate sets**	**Inappropriate reps**
Endurance	2	2	2	1
Hypertrophy	2	5	1	2
Strength	1	2	1	0
Power	1	0	0	0
Total	6	9	4	3

Table 4.7 Identification of the most common training goals and most common misuse of acute variables using protocol analysis.

A comparison of the user sets, reps, load and rest time against the specified guidelines for each training zone is presented in Figures 4.22-4.24. The appropriate training zones for each training zone are highlighted by the shaded zones, instances where users have not trained within the zone are denoted by a red circle. Power and endurance results are combined in Figure 4.24 due to the lower number of subjects training in these zones. The results reflect a decrease in inappropriate use of the acute variables as training moves towards the strength-power end of the strength-endurance continuum. The inappropriate use of rest time is reflected in the pilot study and web based questionnaire, where rest to work ratio was consistently ranked at a low level and only considered important by the more experienced users.

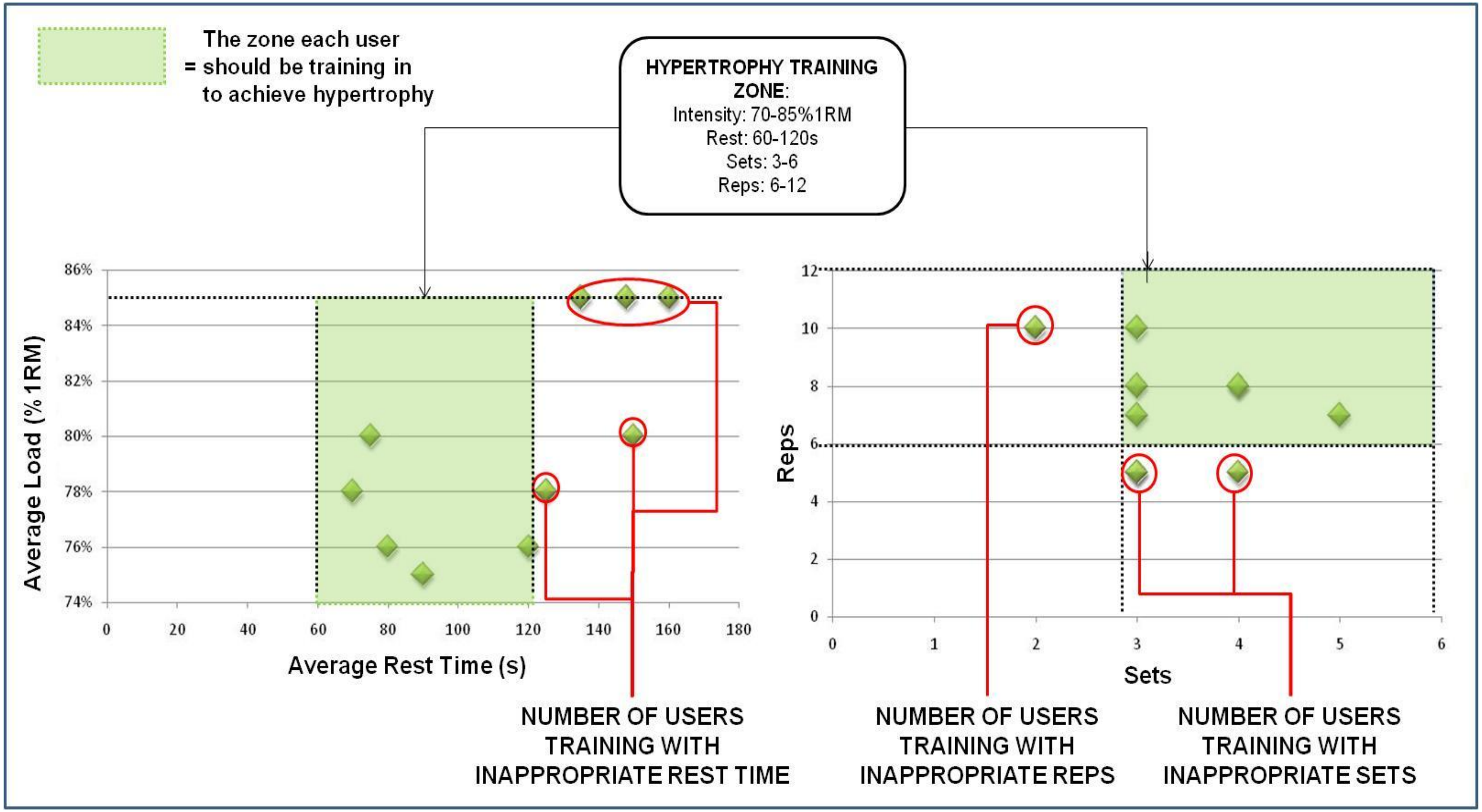


Figure 4.22 Protocol analysis results which identify the numbers of users who do not use the appropriate acute variables to train within the hypertrophy training zone.

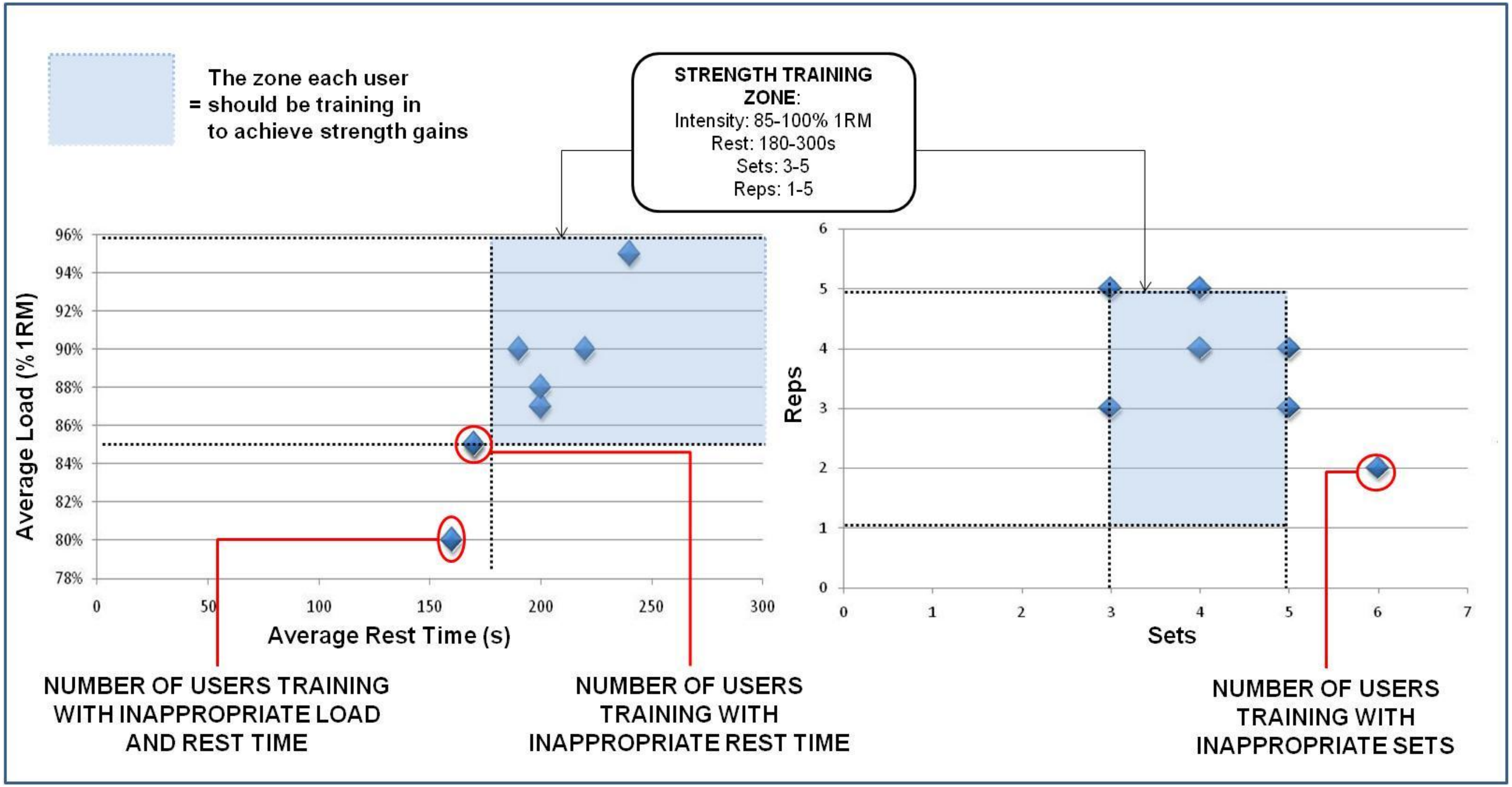


Figure 4.23 Protocol analysis results which identify the numbers of users who do not use the appropriate acute variables to train within the strength training zone.

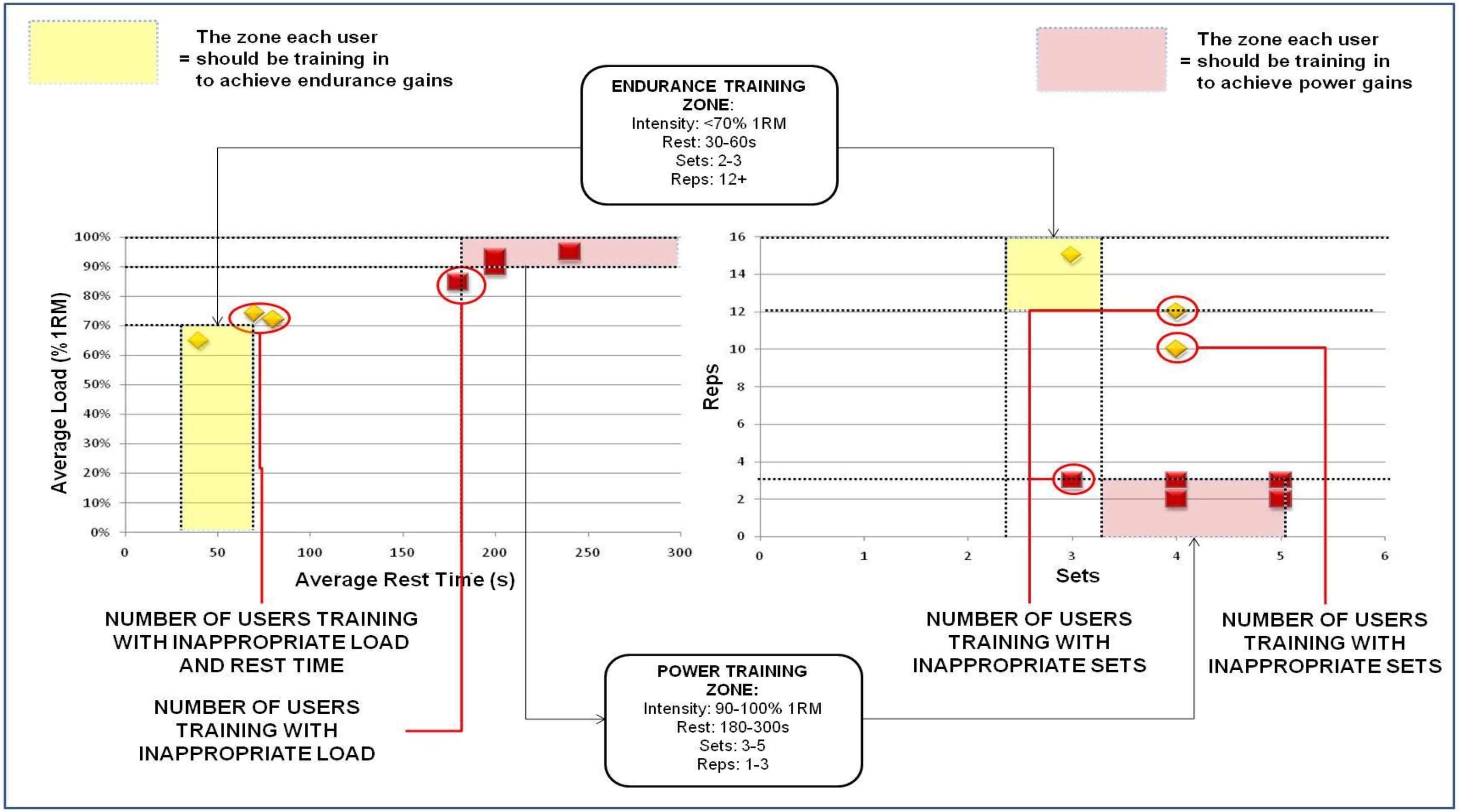


Figure 4.24 Protocol analysis results which identify the numbers of users who do not use the appropriate acute variables to train within the endurance or power training zone.

Whether users consistently under or over estimate required rest time is presented Figure 4.25. The red zone highlights users training for power gain, none of these users under or over estimated the required work to rest ratio and were therefore training effectively. These results support the assumption that the importance of monitoring rest time is appreciated by more experienced users. The average over or under estimation of rest time is also identified in Figure 4.25. Users training for strength gains underestimated the rest time by an average of 10 seconds, whilst those training for hypertrophy and endurance overestimated the rest time by an average of 15 and 22.6 seconds respectively. Therefore, it can be assumed from these results, combined with the written and web based results, that rest to work ratio is a parameter that is not effectively used by less experienced gym users.

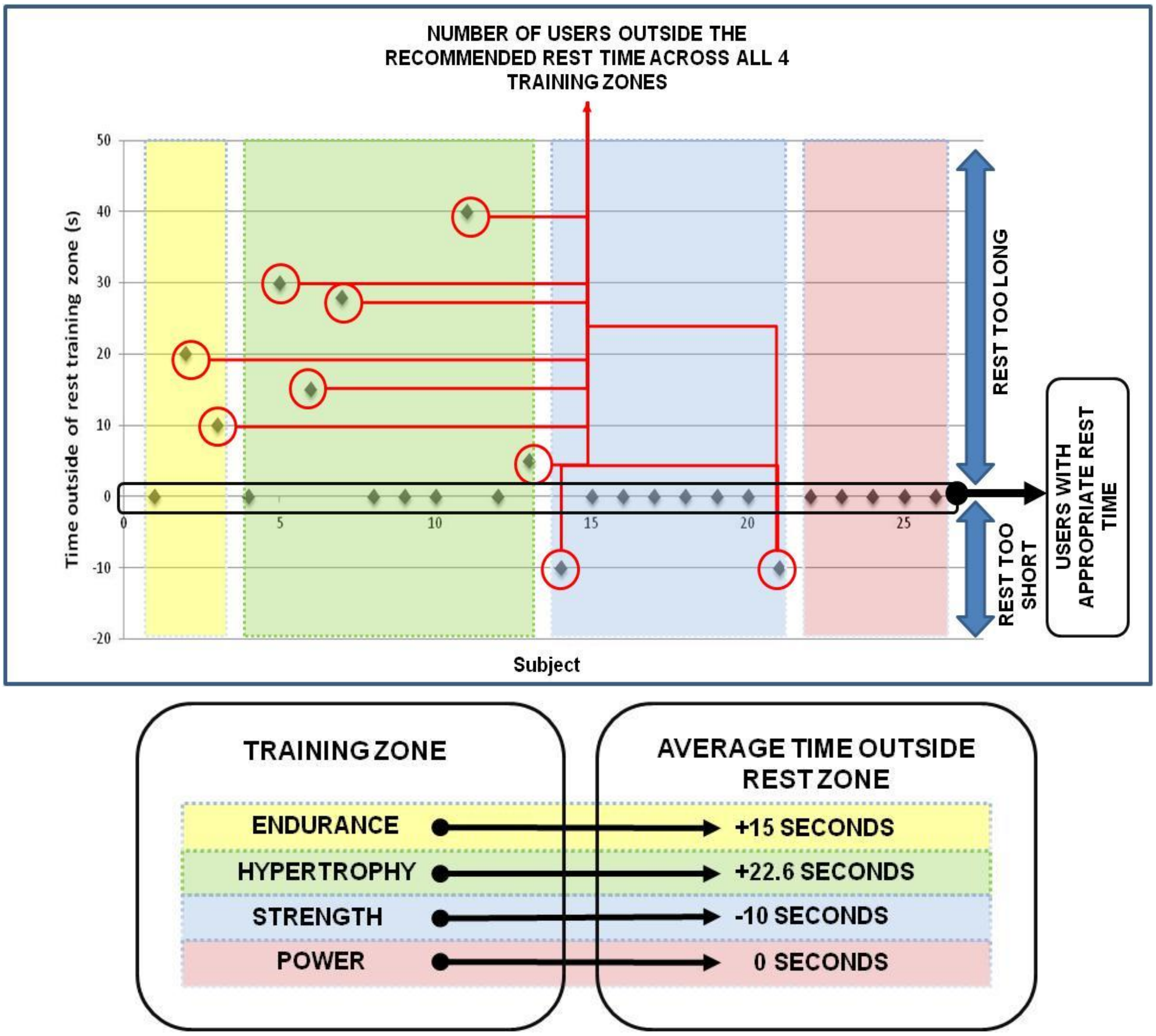


Figure 4.25 Identification of the number of gym users outside the appropriate rest time zone according using protocol analysis.

Protocol analysis in the gym environment successfully investigated issues originally highlighted by the conversational techniques. Users are able to identify what their training goal is, yet over half the sample population (57%) misused one or more of the acute variables to target the training zone, with a majority of misuse accountable to inaccurate rest time. Therefore, it is suggested that in order to support performance monitoring in a gym environment, there is a need to provide work to rest time feedback. Furthermore, this analysis also indicates how users also under or over estimate the sets, reps and load, how this can be controlled and monitored is another area to be considered in the system design.

Overall, it is clear that the most inappropriate use of the acute variables occurred in the hypertrophy training zone, this may be due to the higher percentage of sample population who selected this training. However, 'training for muscle gain' is a common goal for many gym users, whilst training for power may be considered a goal for more experienced users. Training for power requires an appreciation for the both the force and velocity applied to the load, the user requires more technical awareness, therefore it is likely that the more experienced users training for power realise the importance of adhering to a strict work to rest ratio in order for the training goal to be achieved. Although the acute variables do not provide kinetic or kinematic data relating to the exercise execution, they influence whether a user is training effectively according to their target goals and therefore should be considered an important form of feedback.

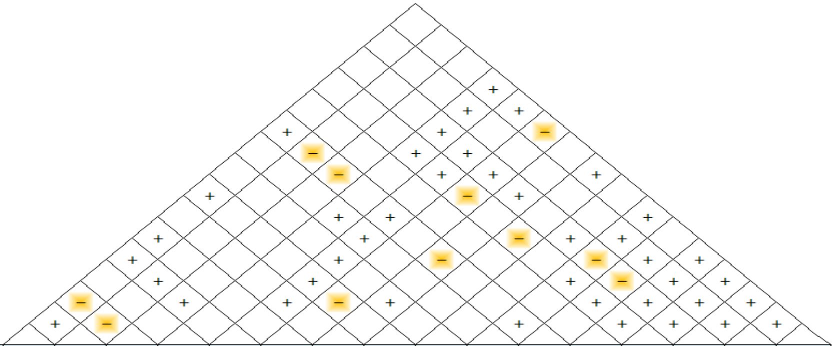
4.7 Resultant user requirements

Using the requirements derived from the re-iterative requirements elicitation process and the competitor overview presented in Chapter 2, a house of quality was produced to determine the relationship between the user requirements and product capability (Bosert 1991). A house of quality is a diagram that stems from Quality Function Deployment (QFD) which uses a correlation matrix to investigate how products should be designed to reflect customer requirements (Hauser 1993). The proposed methodology suggests that each design requirement should be derived from a user requirement, therefore, the HOQ provides a structure against which the designed system can be evaluated later in the project.

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Row #	Customer Importance	Maximum Relationship	Customer Requirements / Functional Requirements	Wireless transmission	Dimensions	Weight	Interface	Technology combined	Sampling rate (Hz)	Withstand high forces	Bandwidth (Mbit/sec)	Durability	Set up time	Suited to a gym environment	Supporting analysis software	Multiple users	Suitable for elite analysis	User friendly	Stroage capability		Myotest	MusclePowerLab	Tendo	Row #
			Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16					
			Direction of Improvement	◇	▼	▼	◇	◇	▲	◇	▲	▲	▼	▲	▲	◇	▲	▲	▲	Customer Competitive Assesment				
1	10	10	Real time feedback	●				●	●		●		○			○	●	○	●		5	0	5	1
2	10	10	Max and average power				●	●		●					●		●				5	5	5	2
3	9	10	Max and average force				●	●		●					●		●				5	0	0	3
4	8	10	Max and average velocity				●	●		●					●		●		●		5	5	5	4
5	7	10	RPD and RFD				●	●		●					●		●		●		3	0	0	5
6	6	10	Readiness to perform				●	●		●					●		●		●		0	0	0	6
7	8	10	Training input feedback				●	○					●	●	●		●		●		0	0	0	7
8	8	10	Variety of exercises	○				●	○	●	○	○	○		○		●	○	○		2	2	2	8
9	6	10	Feedback between sets	●			●	●	○				○	○	●		●	○	○		4	2	1	9
10	5	10	Choice of graphical display				●	○					○	○	●		○	●			3	2	2	10
11	8	10	Bar mounted product	●	●	●		●	●	●	●	●	●	●	●	●	●	●			5	5	5	11
12	10	10	No disruption to session	●	○	○	○	●		○			●	●	●	○	●	●			4	3	3	12
13	10	10	Comparison between sessions	●	○	○	○	●		○			●	●	●	○	●	●	●		3	3	3	13
14	10	10	Bar and body kinematics		○	○	●	●	○	○			○	○	●	○	●		○		1	1	1	13
15	10	10	High accuracy	●	○	○	○	●	●	●	●	●	●	○	●	○	●	○	●		2	1	1	13
			Max Relationship	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	TOTAL SCORE				
			Technical Importance Rating	10	5	10	8	9	7	8	7	6	7	9	8	5	10	10	9	73	47	29	33	

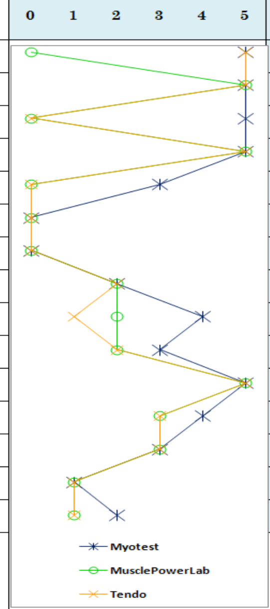


Figure 4.26 House of Quality designed to establish the relationship between the customer and functional requirements in relation to other commercial performance monitoring products.

4.8 Chapter summary

TARGET OBJECTIVES:

- *Collect both qualitative and quantitative data to define user requirements from an elite and recreational perspective.*
- *Re-iterate user requirements to consider user type and level of experience.*

TARGET RESEARCH QUESTIONS:

Which requirements elicitation methods should be combined to promote re-iteration of the user requirements?
Combining conversational and observational requirements elicitation methods allowed concept, process, tacit and explicit knowledge to be captured. The use of a pilot survey, questionnaire and protocol analysis enabled re-iteration of the requirements elicitation methods.

Which exercises are considered to be the most complex?
Conversational and observational analysis methods facilitated the ranking of exercises according to both frequency of use and complexity of execution. The results indicated that the higher the complexity ranking, the lower the frequency ranking. The results presented in Figure 4.27 indicated that the more complex exercises required knowledge and ability to perform exercises with a lower complexity ranking. The Olympic lifts are considered the most complex exercises and are therefore performed less frequently in the gym environment. The power lifts are more frequently performed in a gym environment and are considered less complex.

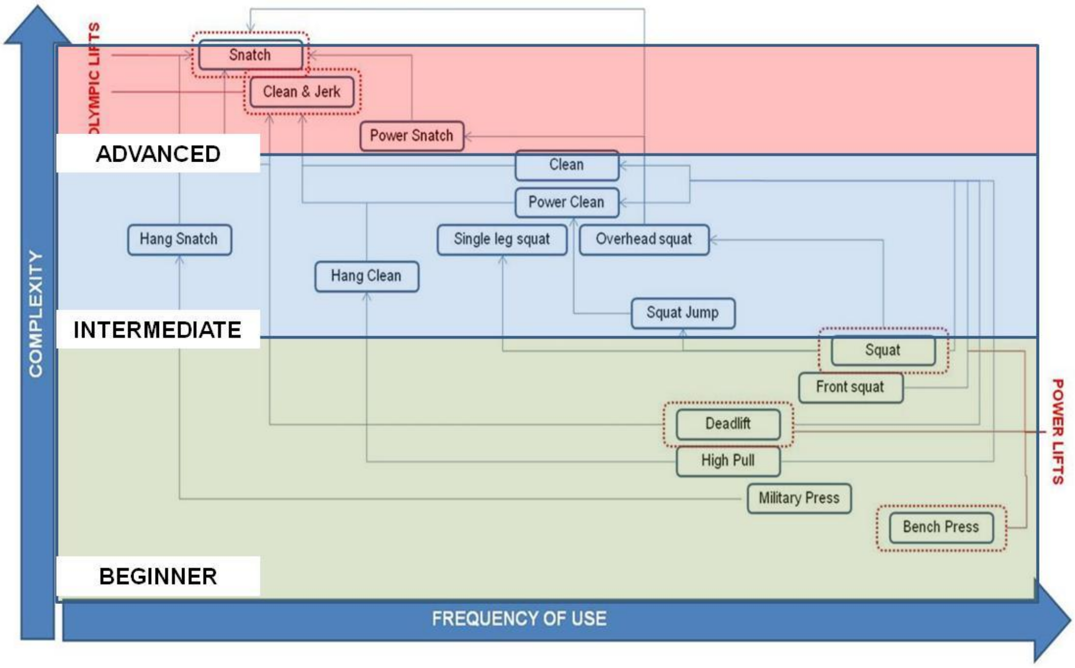


Figure 4.27 Classification of free weight exercises into beginner, intermediate and advanced categories based upon the exercise complexity and frequency of use results derived from the requirements elicitation process.

How does user experience and gender affect the derived user requirements?

There was high correlation between user groups regarding fatigue indicators, with reduced force and speed being identified as most important. Experienced users ranked work to rest ratio as highly important parameters whilst the other user groups felt it was of low importance. Experienced users also had a higher appreciation for the need to consider accuracy of the data as oppose to the aesthetics and comfort. Difference in user level was also identified following protocol analysis. Those training for power adhered to the training zones more than any other user group. The Pearson's correlation coefficient results presented in Section 4.5.4 also indicated that correlation between the novice, intermediate and experienced users does not exist. Therefore, it can be concluded that performance variable importance is affected by user type. Performance variable importance according to male and female opinion differed significantly. Calorie expenditure was rated as the most important variable for females and the least important for males. Novice and female data was significantly correlated, suggesting that a majority of novice users were female, this reduces the credibility of their answers as according to the filtering method, they consider themselves to be recreational users, do not follow a structured program or never visit the gym.

How does re-iteration of the requirements elicitation methods affect the derived user requirements and what are the resultant user requirements?

Both conversational and observational requirements elicitation methods have been used to collect both qualitative and quantitative data. Determining the user experience level allowed the data to be analysed from an elite and recreational perspective using the pilot survey. This was improved further using the web based method which allowed user level to be determined through and/or logic allowing the data to be analysed from a novice, intermediate and experienced level of user. The cross filtering method and subsequent ranking of parameters facilitated identification of differences in gender and user level. A comparison of performance variable ranking using the pilot survey and web based data and the variable ranking achieved using the cross filtering method is presented in Figure 4.28.

Considering the views of different user groups within the sample population has an impact on the perceived importance of performance variables, with 6 of the 7 parameters receiving a change in rank. The change in position is highlighted by a "+ or –" in relation to the original and final ranking. Cross filtering and ranking caused a shift in the ranking order of performance variables when compared to the original data, suggesting that user type does have an effect on results. Protocol analysis also identified the ineffective use of work to rest ratio to implement structured training programs whilst 57% of the sample population misused one or more of the acute variables, either load, work to rest ratio, sets and reps. The finalised user requirements and summary of the knowledge acquired as a result of the chapter research are presented in Figures 4.29 and 4.30 respectively.

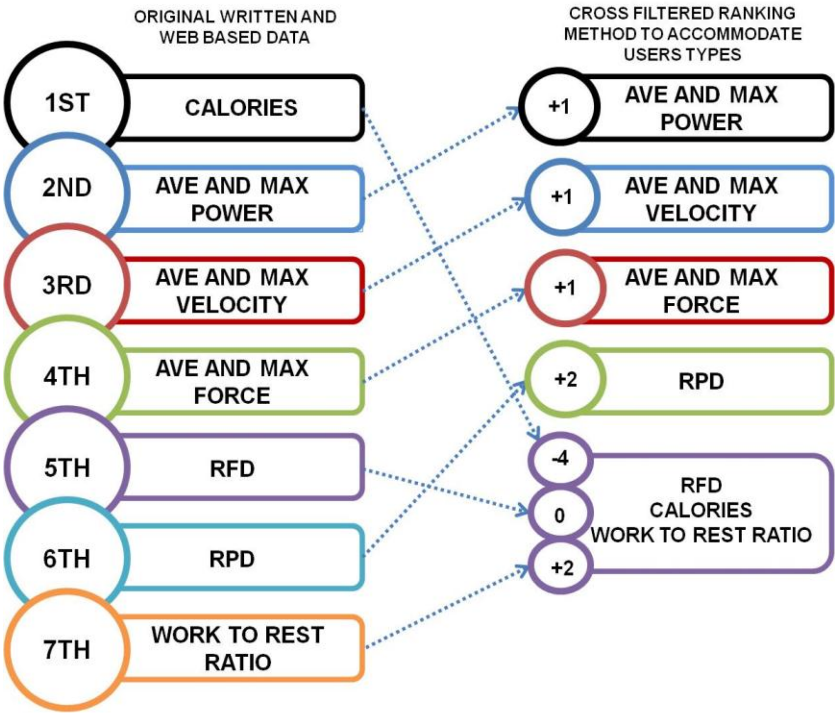


Figure 4.29 The change in performance variable ranking due to the re-iteration of requirements by combining requirements elicitation methods.

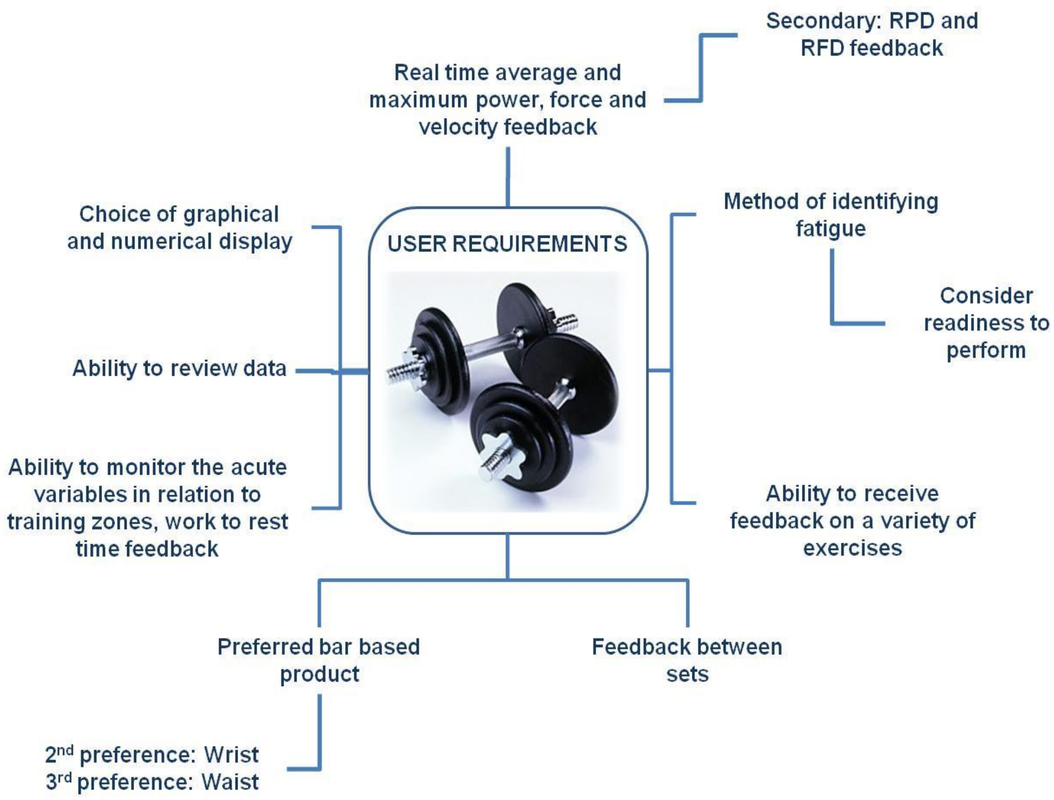


Figure 4.28 Finalised end user requirements derived from multiple requirements elicitation methods.

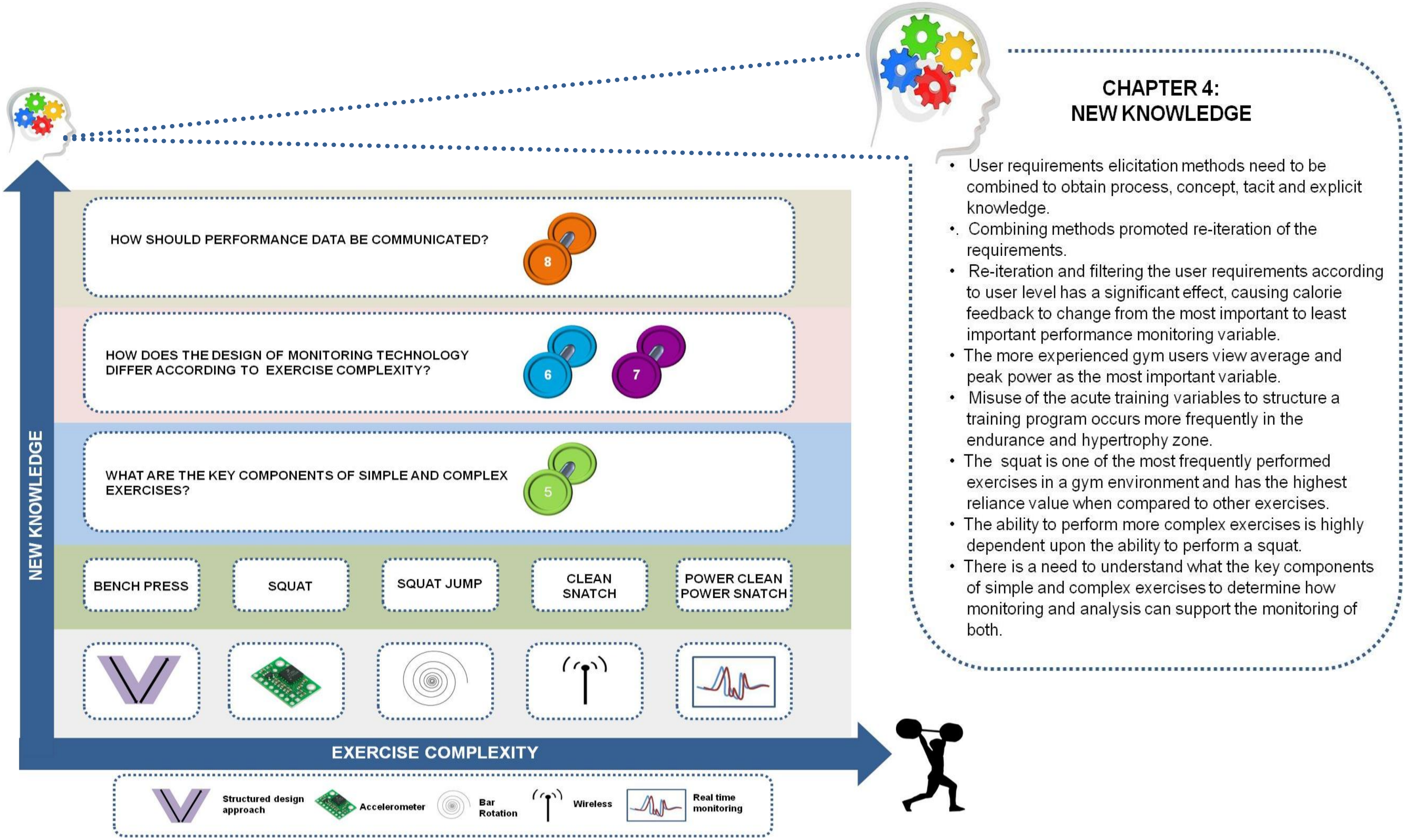
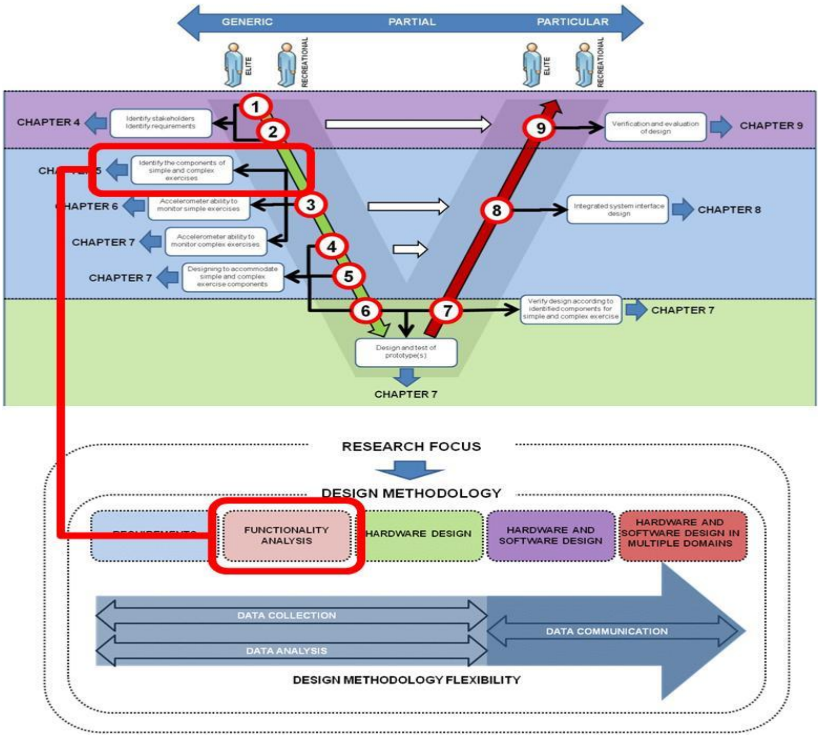


Figure 4.30 The identification of new knowledge acquired and core question findings; exercise complexity ranges from simple exercises (bench press and squat) to complex exercises (Olympic lifts).



Chapter 5

5.0 Identifying the key components of simple and complex exercises

TARGET OBJECTIVE:

Conduct testing to identify the components of simple and complex exercises using video, force platform and accelerometer technology.

TARGET RESEARCH QUESTIONS:

- *Do different exercises exhibit unique acceleration profiles?*
- *What are the key components of a simple and complex exercise?*
- *Do the components differ according to complexity?*
- *Do the components differ according to video, force platform and accelerometer analysis?*
- *Does complexity of the exercise influence the level of monitoring technology sophistication?*

5.1 Introduction

The aim of this Chapter is to investigate whether weight training acceleration profiles differ from those investigated using video and force platform technologies. Whether acceleration profiles exhibit unique key components according to the type of exercise is also investigated. The overall aim is to determine whether the need for more sophisticated technology increases with exercise complexity. The results from Chapter 4 (a continuum plotting frequency against exercise complexity, as illustrated in Figure 5.1), are used to identify whether an exercise is considered simple or complex. Exercises are chosen from each end of the spectrum, ranging from simple and frequently used, to complex and rarely used in a gym environment. The four exercises chosen for analysis are circled in Figure 5.1 covering a range of exercises from the beginner to advanced level. The four exercises are listed below:

- Bench press
- Squat
- Power clean
- Power snatch

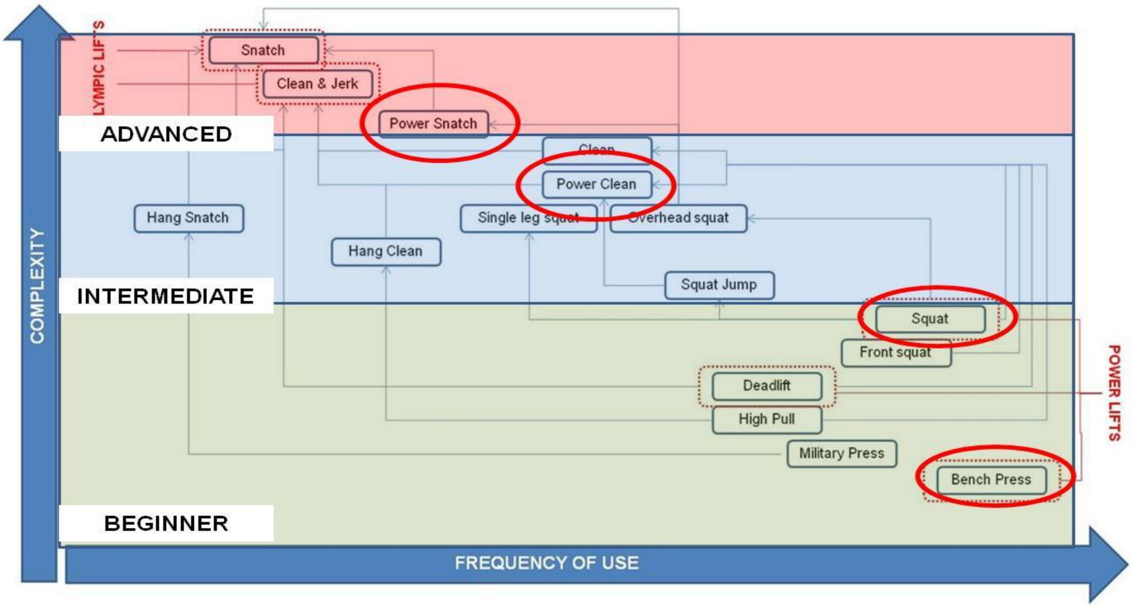


Figure 5.1 Classification of free weight exercises into beginner, intermediate and advanced categories based upon the exercise complexity and frequency of use results derived from the requirements elicitation process.

5.2 Method

Ethical approval was required to conduct the testing discussed in this Chapter. One elite weightlifter performed all four exercises to ensure that correct technique was used. The studies for each exercise were conducted seperately across four sessions. A camera sampling at 50Hz, a Kistler force platform sampling at 1000Hz and an accelerometer sampling at 50Hz developed at Loughborough University were used to monitor the squat, power clean and power snatch. Only video and accelerometer data were collected for the bench press due to the nature of the exercise. Three sets of five reps were completed for each exercise with 2 minutes rest between each. The calculations identified in Chapter 3 (Figures 3.11, 3.12 and 3.16) were used to derive the acceleration from the video and force platform data to compare with the accelerometer data. Force platform analysis focused on the vertical Ground Reaction Force (GRF), the GRF being divided by the system mass to derive acceleration. The acceleration experienced by the system mass (whole body movement + bar) was measured using the force platform, video analysis required double differentiation of displacement data of the bar alone to derive acceleration, whilst the accelerometer was placed on the bar to monitor bar acceleration. Therefore, it was expected that differences would exist between the force platform, video and acceleormeter data. Whether the complexity of the exercise affected the magnitude of the difference between each analysis method was the main focus of each study.

The box-ball analogy discussed in Chapter 3 (section 3.6.4) demonstrated how the orientation of the accelerometer heavily influences the output. Therefore, to prevent misinterpretation of the accelerometer output, the type of movement corresponding to each axis was identified. In the examples discussed, the z axis was aligned to detect movement of the bar in the vertical plane (up and down), the y axis forward and back movement in the sagittal plane and the x axis detected movement along the bar. The orientation of the accelerometer in relation to the bar is illustrated in Figure 5.2.

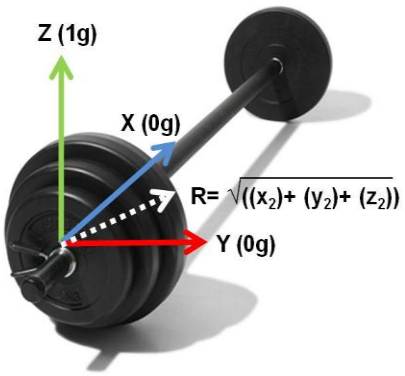


Figure 5.2 Orientation of the accelerometer axes on the bar example calculation of the resultant acceleration vector.

5.2.1 Video filtering

Filtering was required to smooth the video and accelerometer data. Differentiation of video displacement data led to velocity data that exhibited a large amount of noise. A Fast Fourier Transform (FFT) was hence used to determine a cut off frequency (De Levie 2004). A cut off frequency of 10Hz was used to filter the video velocity and acceleration data. An example of the filtering effect on a set of squats is illustrated in Figure 5.3.

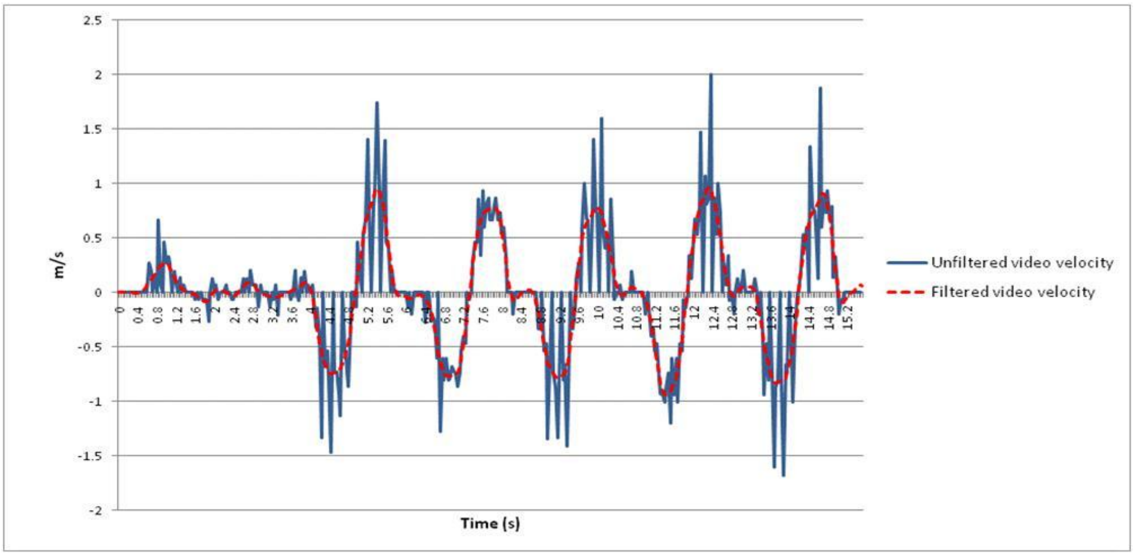


Figure 5.3 The effect of a Butterworth filter on video velocity data

5.2.2 Accelerometer filtering

An example of the acceleration values derived from the accelerometer and converted to the global frame to obtain values relative to gravity (between +1 and -1g) is presented in Figure 5.4. These values lay slightly outside of +1 and -1 g as the accelerometer was not accurately aligned with the global frame. As explained in Chapter 3, this is due to the initial orientation of the accelerometer and cannot be compensated for when the bar is accelerating (i.e in motion) unless gyroscope data is available.

The converted accelerometer acceleration values presented in Figure 5.4 imply that the accelerometer was not perfectly aligned with the global frame. Consequently, a component of gravity was present in both the x and y axis as they do not fluctuate about zero, whilst the z axis fluctuates about -1.2g rather than 1g. This suggests that the accelerometer had misaligned to a point where the z axis was in the opposite direction, (illustrated in Figure 5.5). However, due to the linear nature of the exercise it was assumed that once in position, the accelerometer would have remained in the same alignment throughout the exercise and therefore rotation would not have influenced the data.

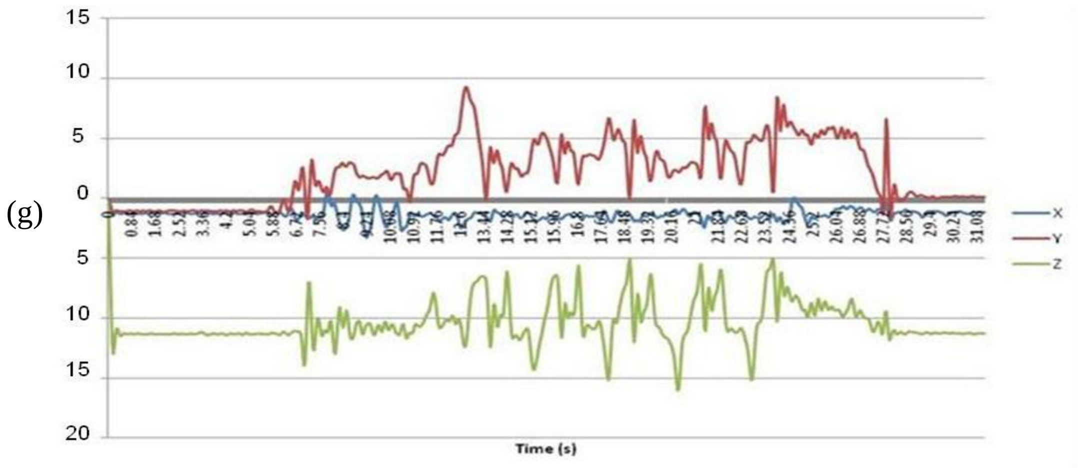


Figure 5.4 Converted node acceleration values exhibiting a slight change in initial orientation and resultant gravity component in the x, y and z axis

As explained in Chapter 3, to gain meaningful data, the resultant force vector must be calculated from the x, y and z components (illustrated in Figure 5.5). The R vector is the force vector that the accelerometer is measuring, whether this is due to the gravitational field or inertial force. The R vector is calculated using the Pythagorean Theorem. An example of the R vector calculation and example squat signal is presented in Figure 5.6. Each exercise required filtering of the accelerometer and video data, the duration of each rep was selected using video analysis, this allowed the corresponding force platform and accelerometer data to be analysed. The data analysis methodology was applied to each exercise. The results are presented in the following sections.

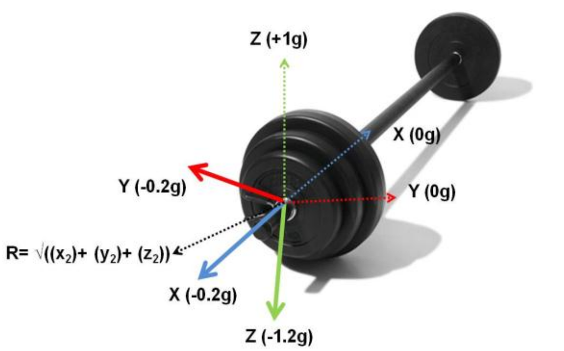


Figure 5.6 Misalignment of the x, y and z axis and calculation of the R vector

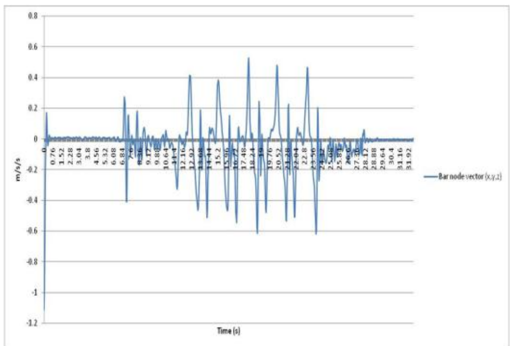


Figure 5.5 Bar node R vector signal

5.2.3 Statistical analysis

To determine whether the bench, squat, power clean and power snatch acceleration profiles derived from the force platform, video and accelerometer were significantly different was investigated using Pearson's correlation coefficient. As outlined in Chapter 4 Section 4.5, the significance level can be used for numerous statistical parametric and non-parametric tests to determine the significance of the results. If the probability is less than or equal to the significance level, then the null hypothesis is rejected and the outcome is said to be statistically significant. Most commonly the 0.05 level (5% level) or the 0.01 level (1% level) is used to determine whether the null hypothesis is rejected. The lower the significance level, the more the data must diverge from the null hypothesis to be significant (Brase 2011).

5.3 Analysis of simple exercises

5.3.1 The bench press

The bench press is an upper body, predominantly linear exercise. An overview of bench press execution is presented in Table 5.1 (ExRx 2011). The bench press was selected due to the linear and simple nature of the exercise and as highlighted in Chapter 4 it is one of the most simple and frequently performed exercises in a gym environment. The teaching points describing how the bench press is executed and how the movement is achieved are listed in Table 5.1. These teaching points indicate that there is an eccentric phase as the bar is lowered to the chest followed by a concentric phase as the bar is raised. Work is done as the bar is raised against gravity.

Teaching points	Joint movement (Dynamic)	Muscles used
Preparation Lie on bench and grasp stirrups attached to low cable pulley on each side. Position stirrups out to each side of chest with bent arm under each wrist. **Execution** Push stirrups up over each shoulder until arms are straight and parallel to one another. Return stirrups to original position, until slight stretch is felt in shoulders our chest. Repeat.	Elbow flexion	Brachialis Biceps brachii Brachioradialis
	Elbow extension	Triceps brachii Anconeus
	Shoulder transverse flexion	Pectoralis major Deltoid (anterior) Coracobrachialis Biceps brachii (short head)
	Shoulder transverse extension	Deltoid (posterior) Latissimus dorsi Infraspinatus Teres minor

Table 5.1 Teaching points, joint movement and muscles used during the bench press (ExRx 2011)

The accelerometer was placed on the bar in the same orientation as that shown in Figure 5.2 with the z axis aligned to the vertical plane. Three reps of a bench press were completed by an elite subject. Video and accelerometer data were collected in a gym environment and force platform data were not collected due to the nature of the lift. An example of the bar trajectory formed by manual digitisation of the bench press is presented in Figure 5.2(a). The bar trajectory follows a diagonal path comprising of a component in the z and y axes. Acceleration was detected on the accelerometer z and y axes. The accelerometer data were converted to the global frame and the vector calculated. The video data were used to identify the start and end of each rep, the resultant identification of each rep in the accelerometer trace is presented in Figure 5.7(b). The signature of each rep is distinctive, a negative peak occurs as the bar is lowered to the chest (i), two positive peaks as the bar is accelerated vertically during the concentric phase (ii) and (iii), followed by a negative peak as the bar decelerates rapidly and returns to the starting position (iv). The repetitive nature of each rep, starting and ending about zero illustrates that rotation of the accelerometer or bar did not occur. The features of each rep are distinctive, detection of the positive peak (iii) may provide a simple and robust method for automatically detecting the number of reps completed.

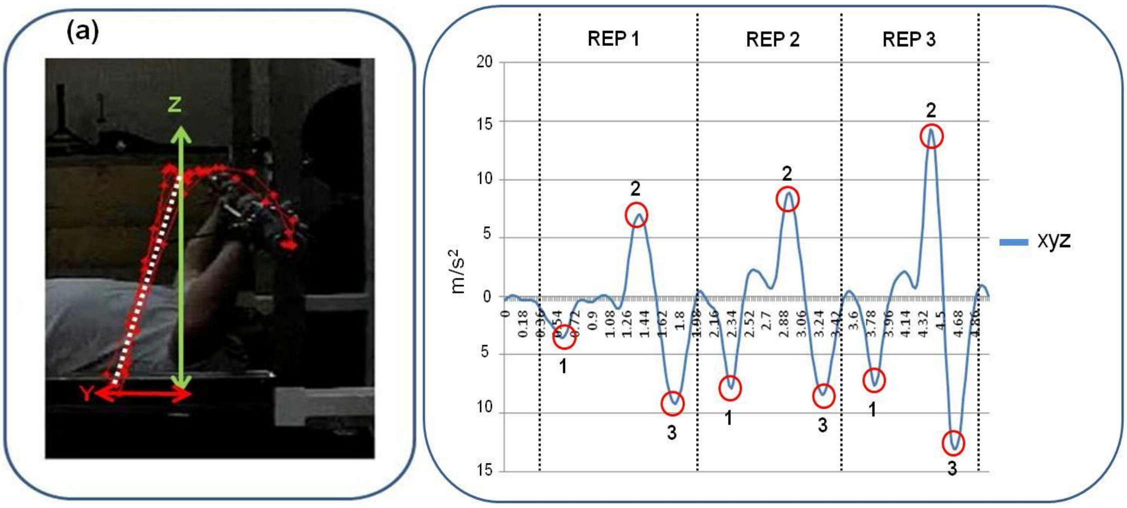


Figure 5.7 Bar trajectory path during the bench press, predominant axes of movement and accelerometer output for three reps of the bench press.

A comparison of the derived video and accelerometer acceleration is presented in Figure 5.8 (b) and (c) respectively. The results indicate that there are three distinct phases evident in both the video and accelerometer profiles. The corresponding movements are highlighted in Figure 5.8 (a), characterised as:

1. **Negative peak:** An initial negative phase as the subject contracts eccentrically and the elbows flex prior to the positive (concentric) phase of the movement.
2. **Positive peak(s):** The positive phase results in a change in acceleration direction until a positive peak is reached.
3. **Rapid deceleration:** The final large negative peak occurs as the bar decelerates rapidly from a peak value to a stationary position with the arms extended. This occurs after the exercise has been completed.

The video trace exhibits a less smooth trace, probably due to the low digitisation frequency and the double differentiation of these data to derive the acceleration. Frequency that is too low causes a loss of accuracy that can affect the profile and peak values. Higher digitisation frequency is required for an accurate comparison. Although the absolute values of the peaks and troughs in Figures 5.8 (b) and (c) (phases 1-3) differ, it is clear that a distinctive, repeatable acceleration profile is produced for each rep of the bench press.

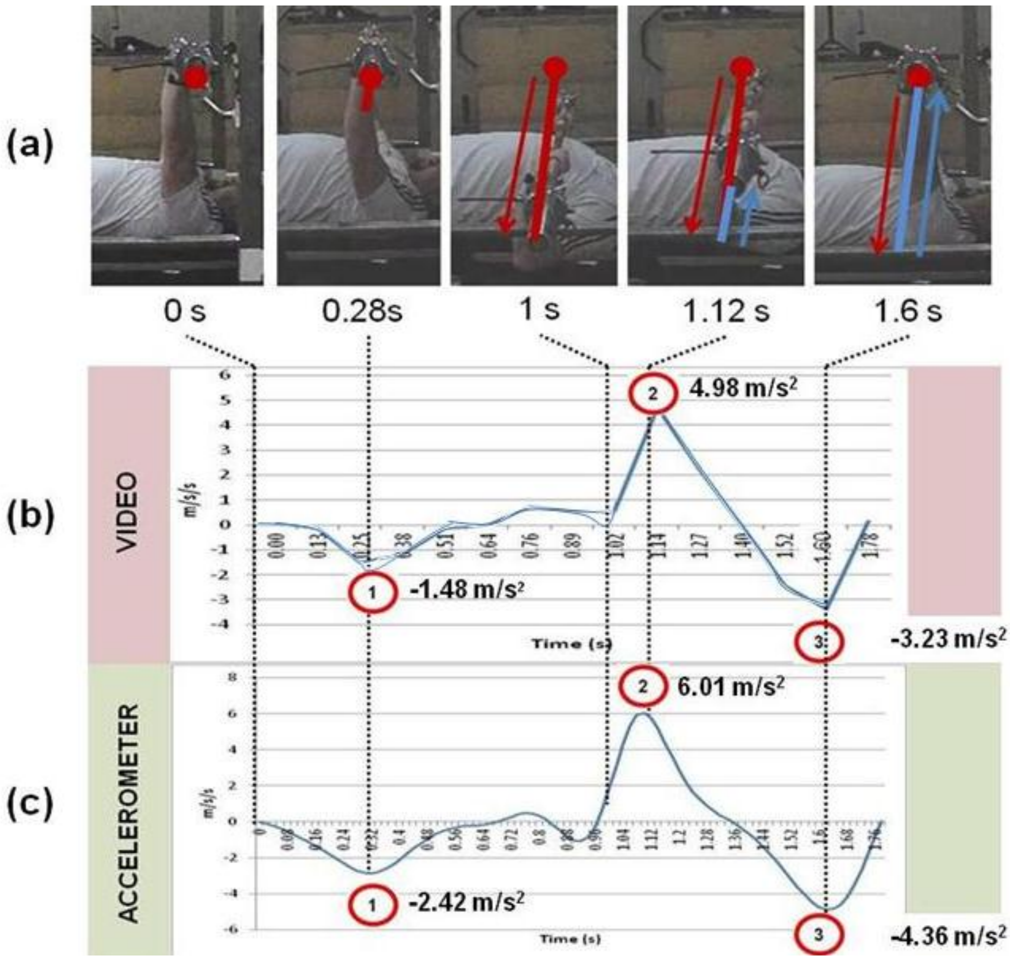


Figure 5.8 Comparison of the acceleration trace derived from video and accelerometer data for the bench press and identification of the key phases in each trace.

5.3.2 The squat

In contrast to the bench press, the squat is a whole body exercise, however, the movement is predominantly linear and the bar does not move independently of the body. Research has shown that squatting with the mass on the shoulders is one of the most widely used training exercises for the development of strength in the lower leg extensor muscles (Rahmani et al 2001, ExRx 2011) or for general fitness and rehabilitation exercises (Mclaughlin et al 1977). An overview of the squat is presented in Table 5.2 (ExRx 2011), the teaching points indicate that in a similar way to the bench press, an eccentric phase is required to lower the bar whilst a concentric phase is required to raise the bar as work is done against gravity. Three reps of a squat were completed by an elite subject, video, force platform and accelerometer data were collected in a lab based environment. An example of the bar trajectory formed following video digitisation of the squat is presented in Figure 5.9(a). The bar trajectory is very similar to the bench press as it does not follow a directly vertical path and components of both the z and y axes are once again present due to the diagonal path.

Teaching points	Joint movement (Dynamic)	Muscles used
Preparation From rack with barbell upper chest height, position barbell on back of shoulders and grasp bar to sides. Dismount bar from rack. **Execution** Bend knees forward while allowing hips to bend back behind, keeping back straight and knees pointed same direction as feet. Descend until knees and hips are fully bent. Extend knees and hips until legs are straight. Return and repeat.	Hip extension	Gluteus maximus Semitendinosus Semimembranosus Biceps femoris (long head) Adductor magnus (ischial fibres)
	Hip Flexion	Iliopsoas Tensor fasciae latae Rectus femoris Sartorius Adductor longus Adductor brevis Pectineus
	Knee extension	Quadriceps femoris
	Ankle plantar flexion	Gastrocnemius Soleus Plantaris Tibialis posterior Flexor hallucis posterior Flexor digitorium longus

Table 5.2 Teaching points, joint movement and muscles used during the squat (ExRx 2011)

The video data were used to identify the start and end of each rep (presented in Figure 5.9 (b)) which details the resultant acceleration trace. Similarly to the bench press, the acceleration trace illustrates that a repetitive signal is produced for each rep, whilst the acceleration values start and end about zero, implying that rotation of the bar did not occur. The squat acceleration profile is less smooth than the bench press but there is more fluctuation between each rep. This may be due to the increased possibility of vibration and tilting of the bar as the squat is a whole body movement rather than upper body alone. The positive peaks presented in Figure 5.9 (b) correspond to the number of reps completed, therefore, as indicated by the bench press data, the positive peaks may provide a method for automatically detecting the number of reps completed.

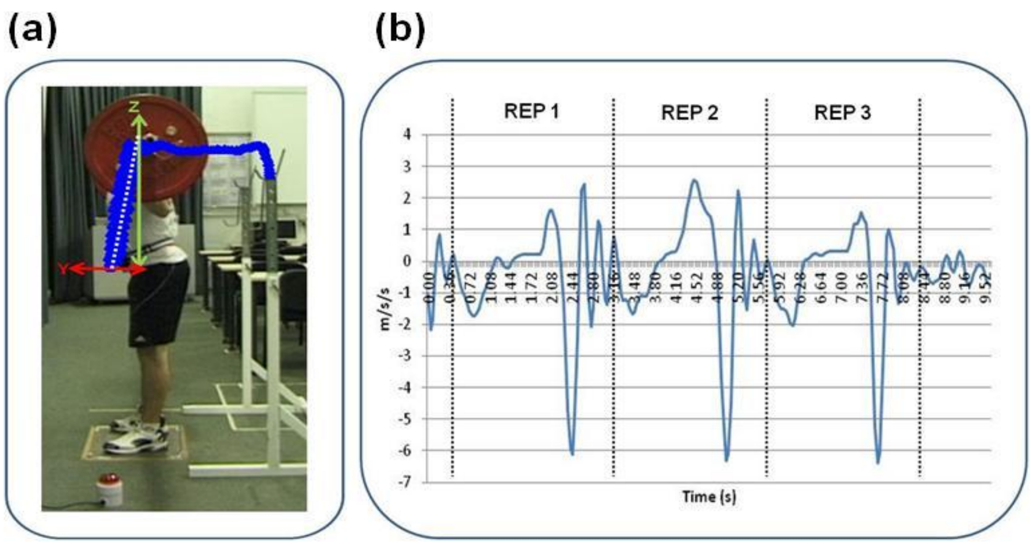


Figure 5.9 Bar trajectory path during the squat, predominant axes of movement and accelerometer output for three reps of the squat.

The Ground Reaction Force data collected using the force platform indicate that the squat produces a repetitive signal similar to the profile derived from the accelerometer. The GRF data also indicates that the subject stays in contact with the ground throughout the movement. A comparison of the force platform data (b), video derived acceleration (c) and resultant acceleration from the accelerometer (d) for one rep is presented in Figures 5.10. The results indicate that all three profiles are highly correlated as each exhibits three distinct phases. The movements corresponding to these phases are also identified in Figure 5.10 (a) and indicate that the key components are similar to those present in the bench press. A negative peak is caused during onset of the eccentric phase

Figure 5.10 ((b1), (c1), and (d1)), a positive peak is reached following the concentric phase Figure 5.10 ((b2), (c2), (d2)) and a final large negative peak is produced as rapid deceleration occurs at the end of the squat Figure 5.10 ((b3), (c3), (d3)).

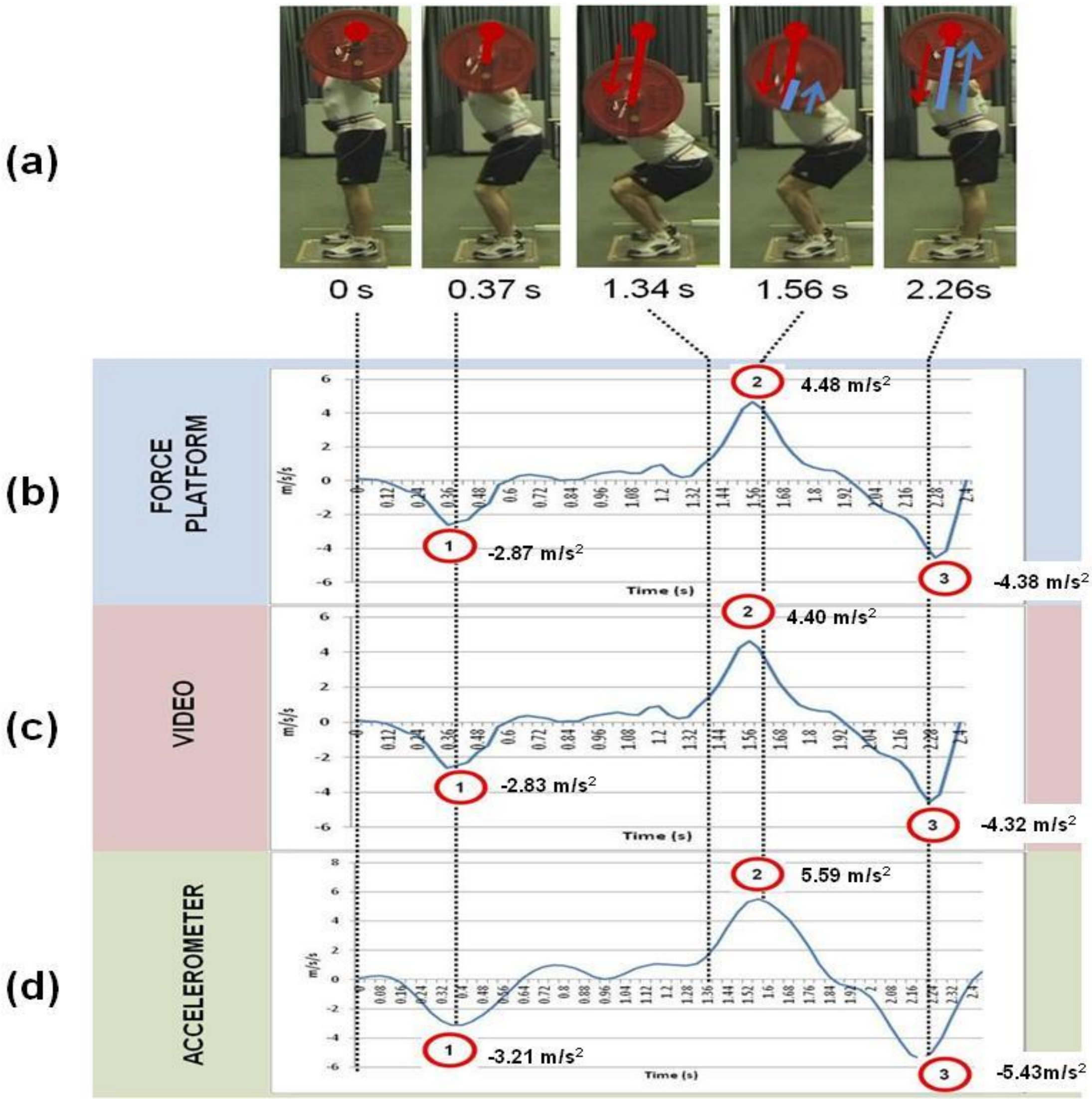


Figure 5.10 Comparison of the acceleration trace derived from force platform, video and accelerometer data for a squat and identification of the key phases in each trace.

5.3.3 Key components of simple exercises

Analysis of simple exercises indicates that the acceleration trace is not unique to each exercise but more to the *type* of exercise and whether the exercises share the same *key components*. Although the squat requires whole body movement rather than upper body alone, it is clear that both exercises have a linear eccentric and concentric component, whilst both produce a diagonal yet linear trajectory that requires movement in the z and y axes. The correlation between the bench press and squat profiles derived from the video, force platform and accelerometer was calculated using Pearson's correlation coefficient (Table 5.3). The correlation between each system for each exercise was also calculated using the same method (Table 5.4). The closer the value is to 1, the higher the correlation existing between the corresponding exercises or monitoring systems.

Compared profiles	Pearson's correlation coefficient	Significant difference
Video bench press v Video squat	0.899**	No
Acc bench press v Acc squat	0.812**	No

Table 5.3 Correlation between the squat and bench press profiles

Compared profiles	Pearson's correlation coefficient	Significant difference
Video bench press v Acc bench press	0.813**	No
Video squat v FP squat	0.966**	No
Video squat v Acc squat	0.862**	No
Acc squat v FP squat	0.876**	No

Table 5.4 Correlation between each monitoring system

The results listed in Table 5.3 indicate that high correlation exists between the bench press and squat profiles (correlation range = 0.812**- 0.899**). Therefore, the bench press and squat profiles do not differ significantly. The results listed in Table 5.4 indicate that there is high correlation between each system (correlation range = 0.813**- 0.966**). Therefore, the bench press and squat acceleration profiles derived from the video do not differ significantly from the force platform and accelerometer profiles. Although the magnitude of the peak values may differ (see Figure 5.11(a) and (b)), the high correlation values listed in Table 5.3 indicate that the results derived from a simple tri-axis accelerometer correlate highly with the video and force platform data. The acceleration profiles therefore exhibit the following key components:

- A linear eccentric phase

- A linear concentric phase

- Constant contact with the ground

- No bar rotation

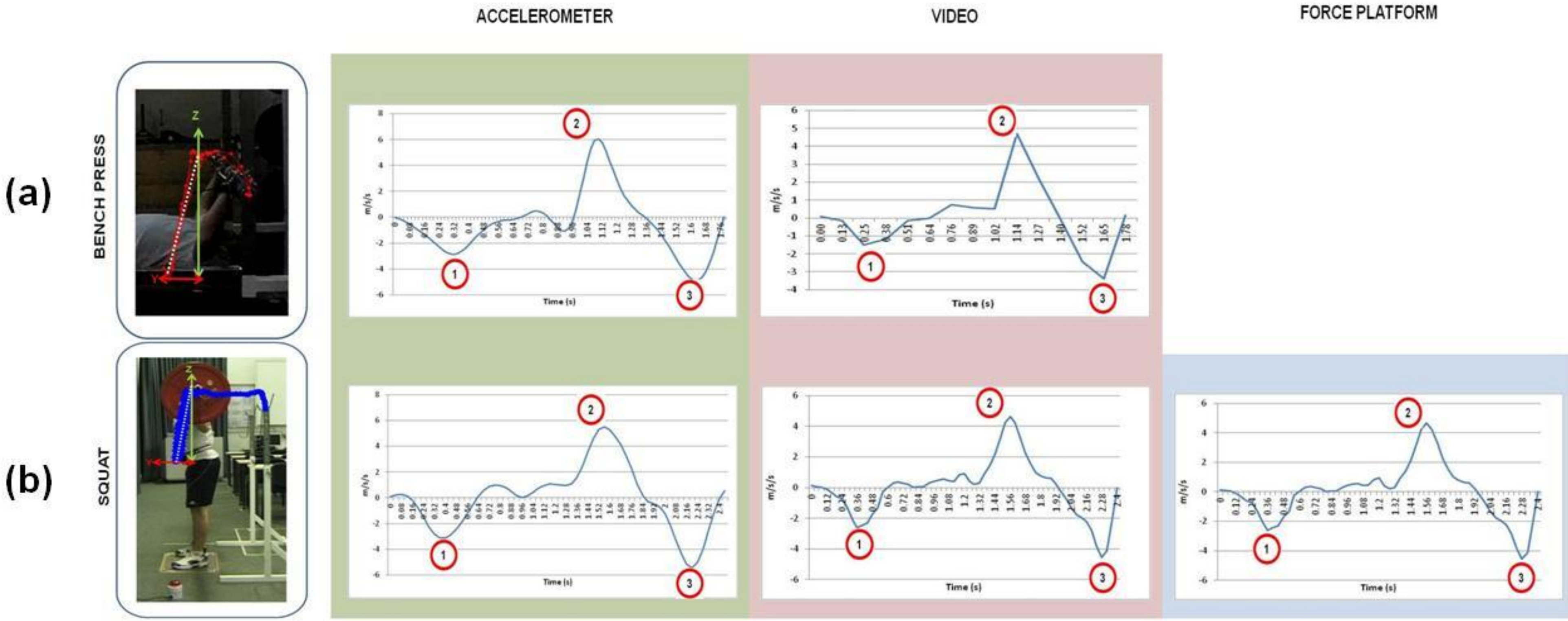


Figure 5.11 Comparison of the bench press and squat acceleration profiles derived from the force platform, video and accelerometer and identification of the key phases during execution.

5.4 Analysis of complex exercises

5.4.1 The power clean

Three reps of a power clean were performed by an elite weightlifter. The power clean is a whole body, multi-planar movement that requires weightlifting experience. It is not an exercise commonly executed in a gym environment by recreational users. The power clean was analysed using video, force platform and accelerometer data. The power cleans were not completed in succession, rather, each rep was performed separately due to the increased complexity. An overview of the power clean is presented in Table 5.3. In comparison to the bench press and squat, there are an increased number of teaching points, further implying that the power clean is more complex exercise. The exercise does not require a loaded eccentric phase, the subject once in position, exerts a force against the bar during the concentric phase until the bar reaches the required height. The power clean also requires a jump to force the bar into position with more power, therefore there is a period in which the subject leaves the ground (flight phase).

Teaching points	Joint movement (Dynamic)	Muscles used
Preparation Stand over barbell with balls of feet positioned under bar pointing forward, hip width apart. Squat down and grip bar with over hand grip slightly wider than shoulder width. Position shoulders over bar with back arched tightly. Arms are straight with elbows pointed along bar. **Execution** Pull bar up from floor by extending hips and knees. As bar reaches knees raise shoulders while keeping barbell close to thighs. When barbell passes mid-thigh, allow it to contact thighs. Jump upward extending body. Shrug shoulders and pull barbell upward with arms allowing elbows to flex out to sides, keeping bar close to body. Pull body under bar, rotating elbows around bar. Catch bar on shoulders before knees bend lower than 90°. Stand up immediately so thighs ride no lower than parallel to floor.	Hip extension	Gluteus maximus Semitendiunosus Semimembranosus Biceps femoris (long head) Adductor magnus (ischial fibres)
	Knee extension	Quadriceps femoris
	Ankle plantar flexion	Gastrocnemius Soleus Plantaris Tibialis posterior Flexor hallucis posterior Flexor digitorium longus
	Shoulder abduction	Deltoid (lateral) Deltoid (anterior) Supraspinatus Pectoralis major (clavicular head)
	Shoulder flexion	Deltoid (anterior) Deltoid (lateral) Pectoralis major (clavicular head) Coracobrachialis Biceps brachii (short head)
	Shoulder external rotation	Teres minor Infraspinatus Deltoid (posterior)
	Shoulder girdle elevation and upward rotation	Trapezius (upper fibres) Trapezius (middle fibres) Levator scapulae Serratus anterior (upper and lower fibres)
	Elbow flexion	Biceps Brachii

Table 5.5 Teaching points, joint movement and muscles used during the power clean (ExRx 2011).

An example of the digitised power clean trajectory is presented in Figure 5.12(a). The red path includes the trajectory of the bar as it is returned to the ground. The green path outlines the trajectory relevant to the lift phase. In contrast to the squat and bench press, the trajectory is not linear. The trajectory exhibits a looping phase as the legs drive the bar in the second phase of the lift. A combination of arcing and rotation occurs. The accelerometer does not maintain the original orientation and understanding which axes experience acceleration is difficult, requiring gyroscope correction. The resultant acceleration profile is illustrated in Figure 5.12 (b). An example of the key movements executed during a power clean is presented in Figure 5.15(a). A comparison of the corresponding force platform (b), video derived acceleration (c), and accelerometer acceleration (d) for one rep is also presented in Figure 5.12.

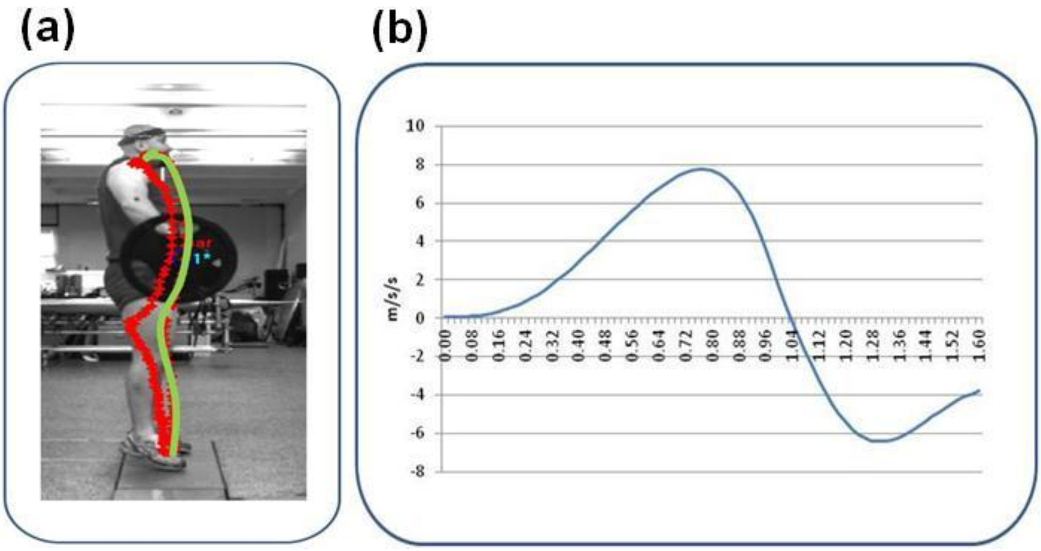


Figure 5.12 Bar trajectory path during the power clean, predominant axes of movement and accelerometer output for one rep.

In contrast to the simple exercises, the acceleration traces show less correlation. Each trace has an initial period of acceleration as the bar is pulled from the ground to the mid thigh. It was expected that the force platform profile would differ due to the flight phase in which the subject leaves the ground and data are not collected. From the GRF profile, two distinct phases can be identified before the subject leaves the ground. The first relates to the first phase of the power clean during the pull from the ground to mid thigh Figure 5.13 (a1). The second pull which requires an aggressive shrug of the shoulders and drive from the legs exerts more force and forces the bar to loop slightly, ready to be caught on the shoulders Figure 5.13 (a2).

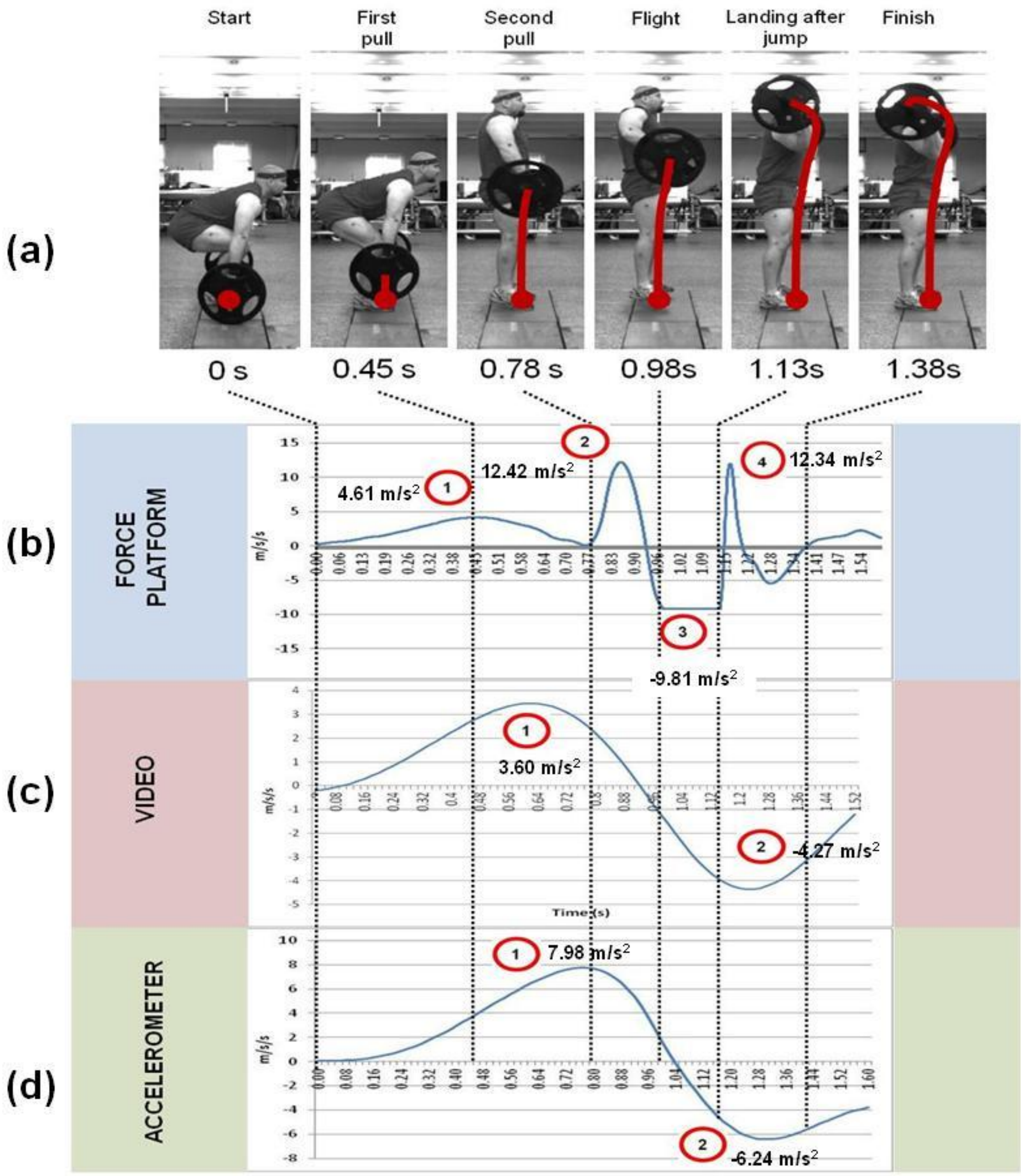


Figure 5.13 Comparison of the acceleration trace derived from force platform, video and accelerometer data for a power clean and identification of the key phases in each trace.

This is reflected by the two peaks that occur before the subject leaves the ground (Figure 5.13 (a3)) and may be a consistent characteristic of the power clean performance. The effect of the subject landing is also detected by the force platform. The force platform acceleration is derived from the GRF, the large increase in force values (from zero to system weight upon landing) causes a significant increase in acceleration. The landing of the whole system weight is indicated by the large positive peak (Figure 5.13 (a4)).

The acceleration derived from the video only considers the acceleration of the bar not the whole body. As the bar does not "land" and the acceleration is not derived from the GRF data, the resultant video derived acceleration profile does not exhibit a second large positive acceleration phase. The video acceleration profile exhibits a positive (Figure 5.13 (c1)) and negative phase (Figure 5.13 (c2)). The negative phase occurs slightly after the bar is lifted half way as deceleration occurs. As the subject leaves the forceplate and reaches maximum height, negative acceleration occurs as the subject returns to the floor and the bar is "caught" on the shoulders. The video digitisation of the bar is maintained throughout the lift, therefore, acceleration of the bar during the flight phase is obtained.

Small deviation from the video acceleration profile is evident in the accelerometer profile. A positive (Figure 5.13 (d1)) and negative phase (Figure 5.13 (d2)) is evident. The positive acceleration phase (Figure 5.13 (d1)) differs in length (1.04 s as opposed to 0.92 s) and magnitude (7.98 m/s^2 as oppose to 3.60 m/s^2), whilst identification of the flight phase, landing or end of the exercise is not possible using the accelerometer trace alone. It is suggested that the increased complexity of the trajectory due to the looping and rotation of the bar and the added vibration caused by the jump take off and landing reduces the accelerometer ability to monitor the power clean accurately. As explained in Chapter 3, rotation of the bar would lead to erroneous acceleration values on the three axes using a simple accelerometer without gyroscopes. The rotation experienced during a complex lift can result from rotation of the bar (as the bar is caught on the shoulders) and arcing of the trajectory. The power clean motion produces both forms of rotation, hence, the probability of inaccurate acceleration data when using a simple system (tri-axis accelerometers and no gyroscopes) is much higher for a complex exercise such as the power clean than when monitoring a simple exercise with the simple system. Whether the effect of rotation is further amplified by a more complex exercise was investigated through the analysis of a power snatch.

5.4.2 The power snatch

Three power snatch lifts were performed by an elite weightlifter. An overview of the power snatch movement is presented in Table 5.4 (ExRx 2011). The same methods used to analyse power clean performance were used to monitor the power snatch.

Teaching points	Joint movement (Dynamic)	Muscles used
Preparation Stand over barbell with balls of feet positioned under bar hip width or slightly wider than hip width apart. Squat down and grip bar with very wide over hand grip. Position shoulders over bar with back arched tightly. Arms are straight with elbows pointed along bar. **Execution** Pull bar up off floor by extending hips and knees. As bar reaches knees back stays arched and maintains same angle to floor as in starting position. When barbell passes knees vigorously raise shoulders while keeping bar as close to legs as possible. When bar passes upper thighs allow it to contact thighs. Jump upward extending body. Shrug shoulders and pull barbell upward with arms allowing elbows to pull up to sides, keeping them over bar as long as possible. Aggressively pull body under bar. Catch bar at arm's length while moving into squat position. As soon as barbell is caught on locked out arms in squat position, squat up into standing position with barbell overhead.	Hip extension	Gluteus maximus Semitendiunosus Semimembranosus Biceps femoris (long head) Adductor magnus (ischial fibres)
	Hip flexion	Iliopsoas Tensor fasciae latae Rectus femoris Sartorius Adductor longus Adductor brevis Pectineus
	Knee extension	Quadriceps femoris
	Ankle plantar flexion	Gastrocnemius Soleus Plantaris Tibialis posterior Flexor hallucis posterior Flexor digitorium longus
	Shoulder abduction	Deltoid (lateral) Deltoid (anterior) Supraspinatus Pectoralis major (clavicular head)
	Shoulder external rotation	Teres minor Infraspinatus Deltoid (posterior)
	Shoulder girdle elevation and upward rotation	Trapezius (upper fibres) Trapezius (middle fibres) Levator scapulae Serratus anterior (upper and lower fibres)

Table 5.6 Teaching points, joint movement and muscles used during the power snatch (ExRx 2011).

The number of teaching points is once again significantly higher than the simple exercises. The power snatch consists of the same two phases of pull executed during a power clean, however, the remainder of the lift requires an overhead lift of the bar. During execution the subject also leaves the ground during the second pull, therefore it is expected that the acceleration traces are similar to that of the power clean during the initial phases. An example of the bar trajectory is presented in Figure 5.14 (a). The trajectory is similar to the power clean, however, a bigger loop is formed as the bar as held in position overhead.

An example of the acceleration profile derived from the accelerometer is presented in Figure 5.14(b). As identified in the power clean analysis, the trajectory exhibits a looping phase as the legs drive the bar in the second phase of the lift. The arcing and rotation is further amplified during the power snatch execution due to the lifting of the bar overhead. A comparison of the force platform (b), video derived (c), and accelerometer accelerations (d) for one rep is presented in Figure 5.15. The corresponding movements derived from the video are also identified to determine if there is correlation between each device and whether the power snatch has key components similar to the power clean.

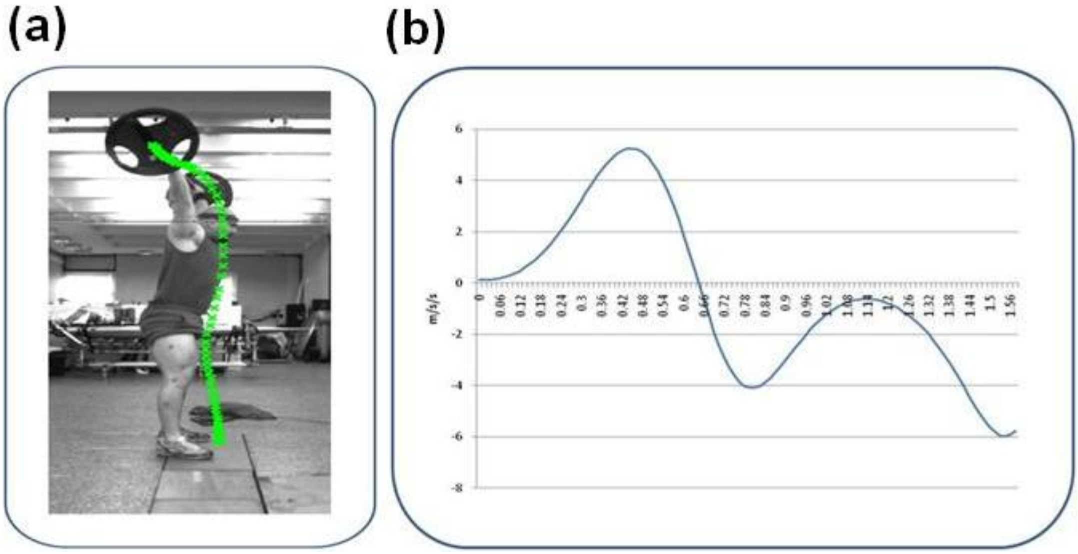


Figure 5.14 Bar trajectory path during the power snatch, predominant axes of movement and accelerometer output for one rep.

The video, force platform and accelerometer traces in Figures 5.15 (b), (c) and (d) are significantly different. The force platform trace (b) has distinctive phases which correspond to specific movements. The two positive peaks correspond to the first and second pull of the power snatch (b1 and b2), the flight phase corresponds to the dynamic jump (b3) whilst the final peak corresponds to the landing phase (b4). These key components are less identifiable in the video acceleration profile (c). The trace clearly has a positive (c1) and negative peak (c2), the positive acceleration occurs during the first and second pull of the power snatch whilst the negative peak occurs during the dynamic jump in which the subject returns to the ground. The accelerometer trace (d) however does not correspond to the video trace as expected. The initial positive peak (d1) is superseded by two negative peaks (d2 and d3), this implies that the bar accelerated against gravity twice (a component that is not shared by the video acceleration trace).

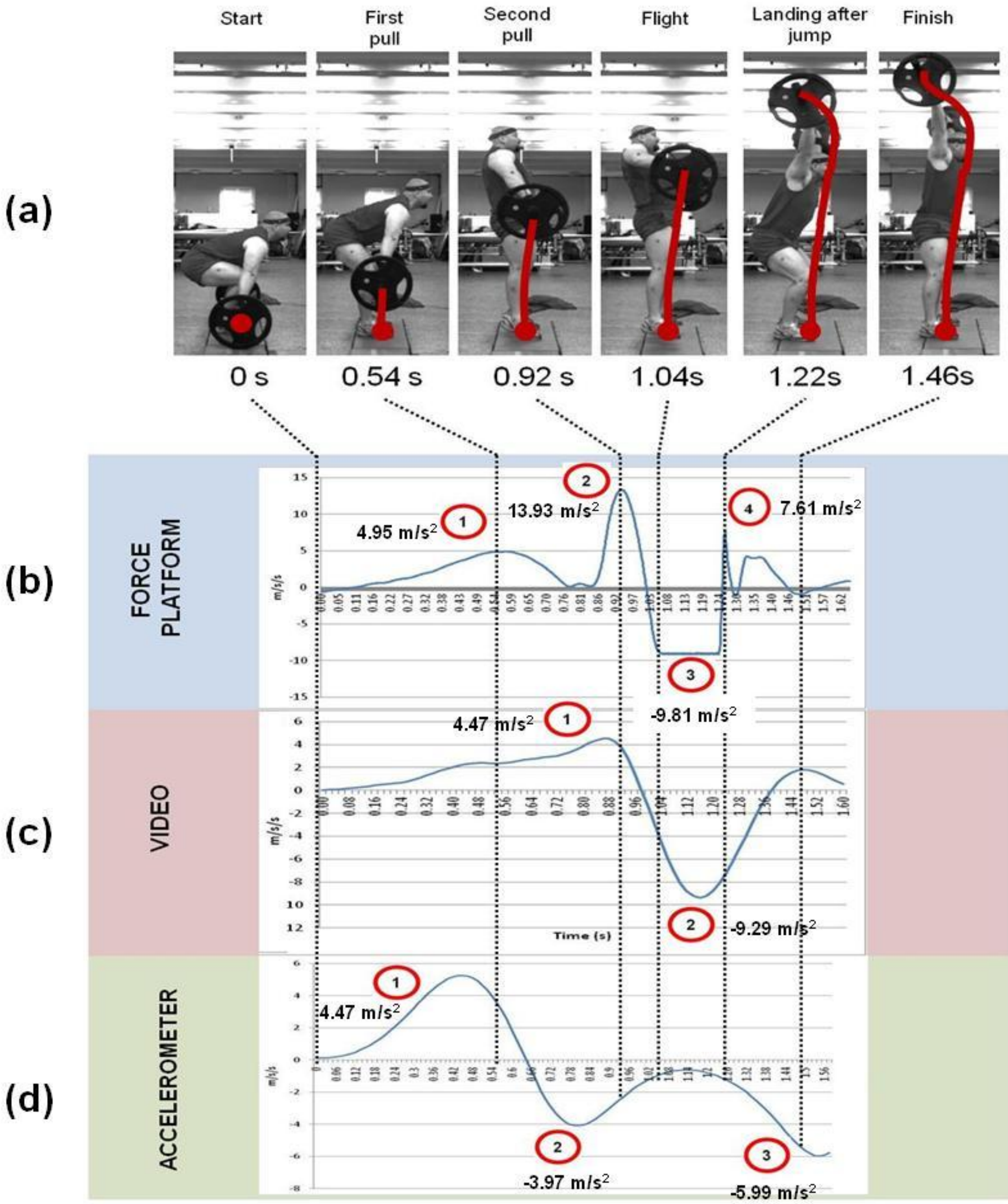


Figure 5.15 Comparison of the acceleration trace derived from force platform, video and accelerometer data for a power snatch and identification of the key phases in each trace.

Whether the power clean and power snatch produced distinctly different acceleration profiles (Table 5.7) and whether the key components differed according to the monitoring device used (Table 5.8) was investigated by comparing each profile using Pearson's correlation coefficient.

Compared profiles	Pearson's correlation coefficient	Significant difference
Video power clean v Video power snatch	0.183	Yes
FP power clean v FP power snatch	0.682	Yes
Acc power clean v Acc power snatch	0.096	Yes

Table 5.7 Correlation between the power clean and power snatch profiles

Compared profiles	Pearson's correlation coefficient	Significant difference
Video power clean v FP power clean	0.183	Yes
Acc power clean v FP power clean	0.096	Yes
Video power clean v Acc power clean	0.582	Yes
Video power snatch v FP power snatch	0.148	Yes
Video power snatch v Acc power snatch	0.175	Yes
Acc power snatch v FP power snatch	0.034	Yes

Table 5.8 Correlation between each monitoring system

The results listed in Table 5.7 indicate that poor correlation exists between the power clean and power snatch profiles derived from the video and accelerometer (correlation range = 0.096 - 0.183). Higher correlation exists between the power clean and power snatch profile when derived from the force platform (0.682). Therefore, the power clean and power snatch profiles differ significantly when derived from kinematic methods. Driving the bar overhead is the main difference between the power clean and power snatch, this can be identified using the video and accelerometer. This distinctive component remains undetected by the force platform as it occurs in flight, resulting in higher correlation between the force platform power clean and force platform power snatch profiles (0.682). The results listed in Table 5.8 indicate that there is poor correlation between each system (correlation range = 0.034 – 0.582). Therefore, the power snatch and power clean acceleration profiles derived from the video differ significantly from the force platform and accelerometer profiles.

The comparison of an acceleration profile for a power clean (a) and power snatch (b) derived from the video, force platform and accelerometer are presented in Figure 5.16. The results indicate that the force platform has four distinct phases present in both exercises:

1. An initial linear drive
2. A second pull
3. A flight phase
4. A landing phase

The second pull identification is not clearly defined in the video and accelerometer data this may be due to the force platform detecting a change in acceleration and force exerted from the lower body that does not cause a distinct reduction in bar acceleration and instead provides the force needed to maintain the acceleration of the bar. The video power snatch acceleration trace (b) is not highly correlated with the power clean (a); the same positive and negative peaks are exhibited during power clean execution, however, in contrast to the symmetry of the power clean, each peak differs in magnitude. The positive phase (b1) is shallower and longer than the sharp peak of the negative phase (b2). This reflects the longer trajectory (see Figure 5.16(a)) and resultant positive acceleration required to drive the bar overhead. A large looping phase increases the negative acceleration required to catch the bar overhead.

The accelerometer data deviates from the video data during the power snatch more than the power clean resulting in higher correlation between the video and accelerometer power clean profiles (0.582) than power snatch profiles (0.175). The reduction in correlation is attributed to the non-linear trajectory which causes rotation of the bar to occur. The power snatch requires slightly more rotation than the power clean due to the need to drive the bar overhead. As explained in Chapter 3, rotation of the bar can cause an erroneous acceleration output when using a simple tri-axis accelerometer without gyroscopes.

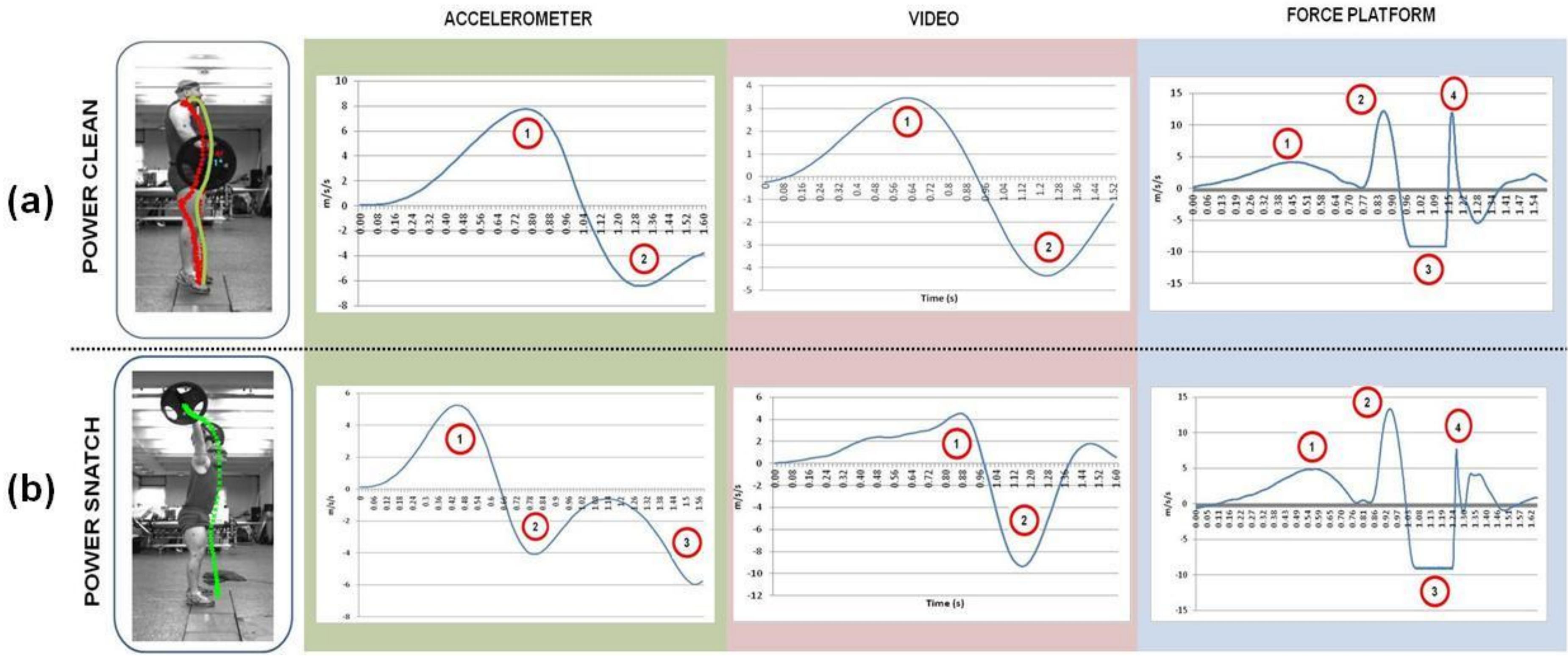


Figure 5.16 Comparison of the power clean and power snatch acceleration profiles derived from the force platform, video and accelerometer and identification of poor agreement between key components.

The rotation experienced during a complex lift can result from rotation of the bar (as the bar is caught on the shoulders) and arcing of the trajectory. As identified in Figure 5.17, the power clean (a) and power snatch (b) produce both forms of rotation; therefore the probability of inaccurate acceleration data is much higher for a complex exercise without gyroscope correction. The two types of rotation acting upon the bar throughout the power clean and power snatch movement is identified in Figure 5.17. The rotation increases as the looping phase begins following the second pull and the bar is caught on the shoulders or overhead. The corresponding video and accelerometer profiles illustrate that deviation of the accelerometer trace from the video trace for the power snatch is higher than the power clean resulting in reduced correlation (power clean correlation value = 0.582 and power snatch correlation (0.175))

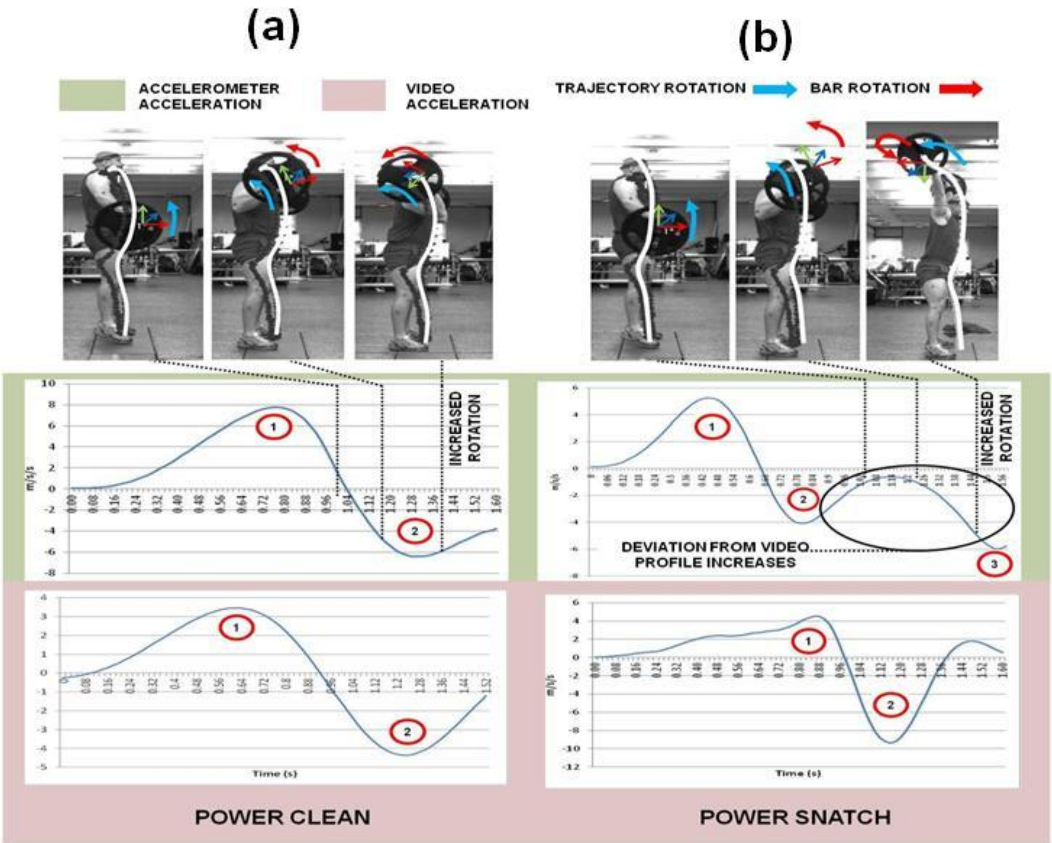


Figure 5.17 Trajectory and bar rotation occurring during the power snatch and power clean and resultant reduced correlation between the video and accelerometer acceleration profiles

The correlation between the video and accelerometer when monitoring simple exercises (bench press (0.813**) and squat (0.862**)) indicate that significant difference does not exist. The decrease in correlation when monitoring the power clean (0.582) and power snatch (0.175) indicates that rotation has a significant effect on the accelerometer profiles and a simple tri-axis accelerometer without gyroscopes does not accurately monitor complex exercises. The non-linear characteristic of the power clean and power snatch trajectory reduces the correlation between each exercise and indicates that *rotation is a key component* of both complex exercises. The key components identified using force platform and video analysis are as follows:

- Linear concentric phase

- Second pull phase

- Dynamic jump

- Landing phase

- Non linear trajectory

- Trajectory and bar rotation

5.6 Brief Chapter summary

TARGET OBJECTIVE:

Conduct testing to identify the components of simple and complex exercises using video, force platform and accelerometer technology.

TARGET RESEARCH QUESTION:

Do different exercises exhibit unique acceleration profiles?

Although the bench press and squat are different exercises, the acceleration profiles exhibit high correlation (0.798** – 0.899**). This is attributed to the linear concentric and eccentric phase without bar rotation which are key components of simple exercises. The power clean and power snatch acceleration profiles exhibit poor correlation when derived from the video and accelerometer (0.096 – 0.182), whilst the force platform power clean and power snatch acceleration profiles show higher correlation (0.682). The distinguishable phase of the power snatch (the overhead drive) occurs when the subject is in flight and is therefore undetected by the force platform. The overhead drive is evident in the video profile, whilst the rotation increases the error in the accelerometer profile. The bench press and squat exhibit similar acceleration profiles due to a linear nature that does not cause bar or trajectory rotation. Therefore, the correlation between acceleration profiles differs according to the key components and complexity of the exercise.

What are the key components of a simple exercise?

The key components identified from the bench press and squat analysis are listed below.

- Linear eccentric phase
- Linear concentric phase
- Constant contact with the ground
- Little or no bar and trajectory rotation

What are the key components of a complex exercise?

The range of key components vary according to the level of exercise complexity. The power snatch and power clean are at the end of the complexity spectrum, the more key compononts listed below that an exercise requires, the higher the complexity of the exercise.

- Linear concentric phase
- Second pull phase
- Dynamic jump
- Landing phase
- Non linear trajectory
- Trajectory and bar rotation

Do the components differ according to complexity?

The number and type of key components differ from one end of the complexity spectrum to the other. The most simple exercises do not require the subject to jump and have a linear trajectory that does not inflict rotation on the bar. The most complex exercises require a dynamic jump, a non-linear trajectory and cause both bar and trajectory rotation.

Do the components differ according to video, force platform and accelerometer analysis?

The mean correlation between the video and accelerometer profiles decreases from 0.838** (no significant difference) for the simple exercises, to 0.379 (significant difference) for the complex exercises. The mean correlation between the video and the force platform profiles decreases from 0.966** (no significant difference) for the simple exercises to 0.166 (significant difference) for the complex exercises. Finally, the mean correlation between the accelerometer and force platform profiles decreases from 0.876** (no significant difference) for the simple exercises, to 0.065 (significant difference) for the complex exercises. Therefore, the agreement between technology decreases as exercise complexity increases. High correlation exists between the video, force platform and accelerometer profiles for simple exercises that do not require a dynamic jump and have a bar trajectory that moves with the whole body or moving body part. If a jump is required, the force platform exhibits a flight and landing phase that is less visible in the video and acceleormeter trace. If the bar moves independently of the body and rotation of the bar occurs, the video and accelerometer detect accelerations that may be undetected by the force platform.

Does complexity of the exercise influence the level of monitoring technology sophistication?

A simple tri-axial accelerometer does not account for the rotation of the bar, therefore, a gyroscope is required to monitor accurately complex exercises that cause bar and trajectory rotation. Force platform technology provides additional performance data for exercises that are explosive and require a dynamic jump due to the visibility of the flight and landing phase. Furthermore, the forces generated by the lower legs during the first and second pulls enable distinction of the phases which are less defined using video and accelerometer analysis. However, the full bar acceleration profile cannot be ascertained from the force platform alone due to the loss of data as the subject leaves the ground (flight phase). Therefore, the power clean and power snatch produce very similar acceleration profiles when derived from the force platform. Combining technology may provide the most accurate method for monitoring complex exercises as the video and accelerometer data provide additional data relating to the bar trajectory throughout the whole movement. As the exercise complexity, dynamic jump requirement and independent movement of the bar increases, the need to combine monitoring technology is increased.

The new knowledge acquired as a result of the research conducted in this Chapter is summarised in Figure 5.18. According to the structured methodology outlined in Chapter 2, decomposition is required to investigate the design requirements and system capability. A breakdown of the analysis is required to identify how the design of a monitoring system may change according to the application. Detailed analysis of a simple exercise using a simple tri-axial accelerometer to determine the relative and absolute validity is required before analysis of complex exercises can be considered.

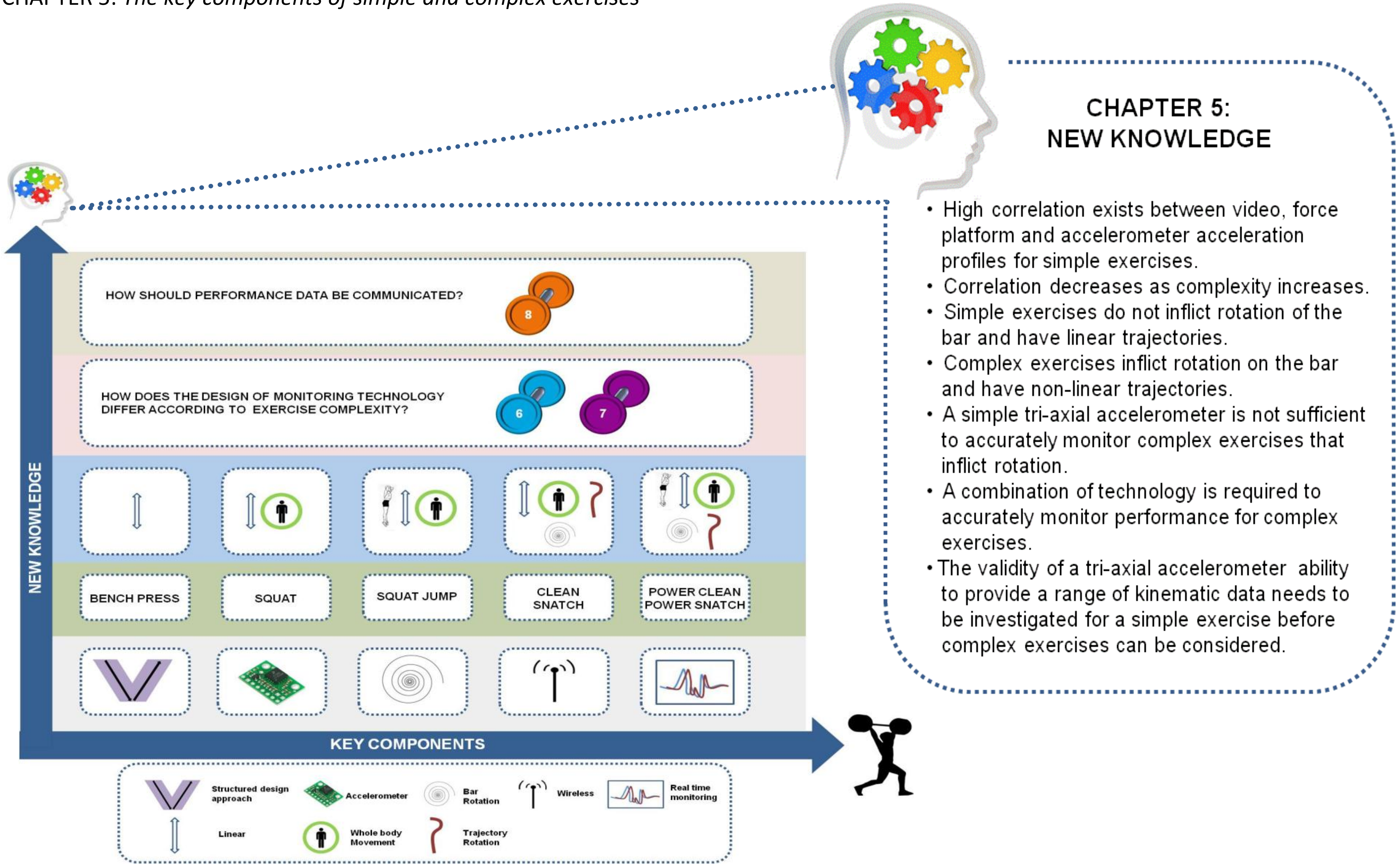
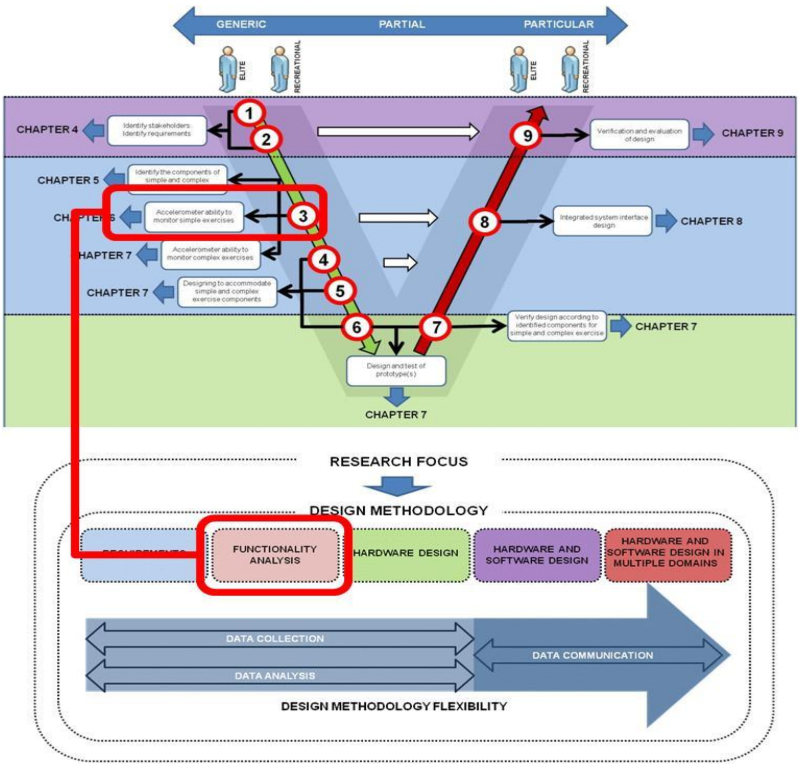


Figure 5.18 The identification of new knowledge acquired as a result of the Chapter and core question findings; the number of key components increases as exercise complexity increases.



Chapter 6

6.0 Monitoring simple linear exercises in the resistance training domain

TARGET OBJECTIVE:

Analyse the execution of simple linear exercises to determine the ability of a simple tri-axis accelerometer (without gyroscopes) to monitor simple linear exercise.

TARGET RESEARCH QUESTIONS:

- *Does an accelerometer exhibit high correlation with video analysis when monitoring simple exercises?*
- *Does accelerometer location affect correlation with video analysis?*
- *What are the advantages and disadvantages of using force platform, waist mounted and bar mounted accelerometers to monitor simple exercises?*
- *What are the resultant design implications of the conducted studies?*

6.1 Introduction

Accurate collection of force and power production is fundamental to sports training. A recent study (Crewther 2011) compared the use of a commercially available linear position transducer (LPT) and an accelerometer to a force platform during a squat jump with varied loads. The results showed that across all loads the linear positional transducer and accelerometer peak force (PF) and peak power (PP) results were moderately to strongly correlated with the output from the force platform ($r = 0.59$-0.87 and $r = 0.66$-0.97 respectively ($P \leq 0.05$-0.01)). It was hypothesised that the systems would show high *relative validity* (correlation) but would differ in *absolute validity* (mean results). The results confirmed the hypothesis of strong relative validity for each kinematic system. However, it was found that the estimates did provide some large random values, particularly with the lowest loads. Furthermore, other variables such as peak velocity, peak acceleration, time to peak velocity, force, acceleration and power were not investigated. Whether kinematic systems can still provide relative validity to calculate a range of variables other than peak force and peak power as well as the determination of the absolute validity is yet to be determined.

The studies conducted in Chapter 5 identified that simple accelerometer technology i.e without the use of gyroscopes, could be used to monitor performance within a gym environment for linear based exercises using the acceleration profile alone as an indicator of repetitions. However, integration errors and failing to monitor the orientation of the accelerometer throughout the lift, could cause large errors in subsequent complex lifts and velocity reliant performance variables. An understanding of the profiles generated by multi-planar and linear movement was gained and correlation between the acceleration profiles (relative vaildity) derived from each analysis method was investigated in Chapter 5. Whether high correlation exists between the force platform, video and accelerometer data when other performance variables are calculated (such as peak acceleration, force, velocity and peak power) is yet to be investigated in more detail. The two studies discussed in this Chapter aimed to investigate the *validity* (i.e the accuracy of the outputs) of the accelerometer data in relation to other kinematic methods during the execution of a squat and squat jump. Two structured studies were conducted with the aim of characterising a simple linear exercise (the squat) and a more complex linear movement (squat jump) using accelerometer technology.

6.2 Method

Eight healthy subjects (five male and three female) with a mean age of 23.9 ± 2.3 years and body mass of 78.8 ± 25.4kg (2 Std Devs) were recruited to conduct both studies. Case study 1 examined the validity of two triaxial accelerometers (kinematic systems) located on the bar and waist and one force platform (kinetic system) in relation to video analysis. Case study 2 examined the validity of one triaxial accelerometer located on the waist and one force platform in relation to video analysis. A camera sampling at 50Hz, a Kistler force platform sampling at 1000Hz and two accelerometers sampling at 50Hz developed at Loughborough University were required to complete both studies. The testing set up is illustrated in Figure 6.1. The camera was positioned to provide a side profile of the participant in the sagittal plane. Synchronisation of the accelerometer(s) and video was achieved through the use of a TTL trigger and LED within camera view, whilst the forceplate was manually activated simultaneously with the accelerometer trigger. The overall testing procedure involved assessment of squat and squat jump performance using the kinetic and kinematic systems.

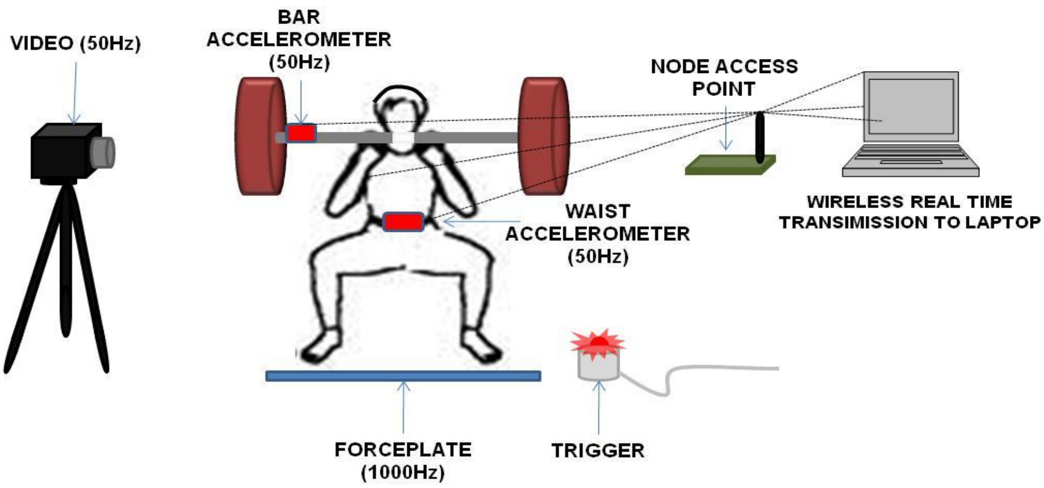


Figure 6.1 Equipment set up for testing

Similarly to the testing conducted in Chapter 5, acceleration of the system mass (body and bar) was detected by the force platform, video analysis required double differentiation of displacement data of the bar and waist to derive acceleration, whilst an accelerometer was placed on the bar and waist to monitor bar and body acceleration. The force platform provides the most accurate form of analysis of the system mass movement due to the high sampling rate and reduced probabilty of human error (such as digitsation error), whilst double differentiation of positional data using video analysis increases the noise present in the signal (Kopecky 2007). However, in the absence of linear positional transducers (LPT's), video data was used as a 'base' method to understand the movement of the bar and body seperately through digitisation of the waist and bar movement where the accelerometers were mounted. The results from Chapter 5 also indicated the need to identify and separate each repetition before the analysis to reduce integration error. Therefore the steps identified in Figure 6.2 were followed to analyse the data.

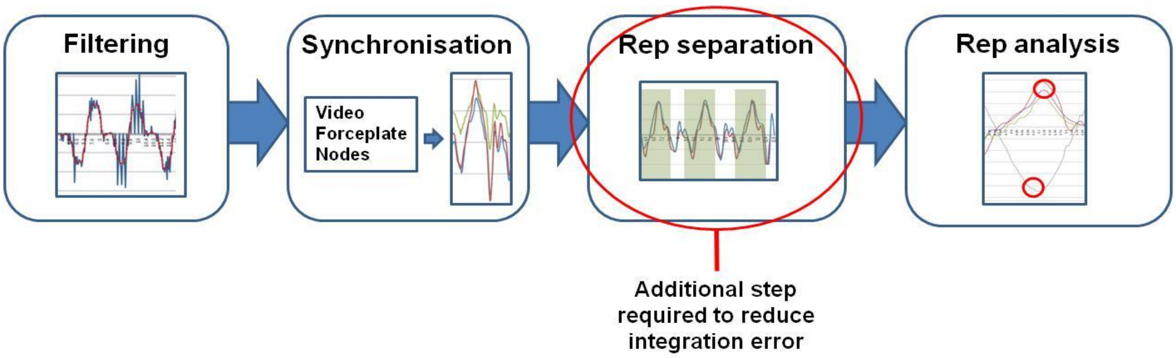


Figure 6.2 The steps of analysis originally identified in Chapter 5 with an additional step of rep separation required before calculation of kinematic variables to reduce integration error.

6.2.1 Statistical analysis

The force platform and accelerometer derived performance variables were statistically compared to the video derived results. Whether significant difference existed between the video-force platform, video-bar mounted accelerometer and video-waist mounted accelerometer was determined using the performance variable mean, standard deviation (SD) and standard error between means (SEM). A significance value (sig value) less than 2 indicates that no significant difference exists between the compared means

(Everitt 2003). The difference between the video and force platform and video and accelerometers was also calculated and the mean derived. The mean percentage difference is listed for each variable to quantify the difference in relation to the original value derived from the video allowing for comparison between different parameters (such as comparing acceleration (m/s^2) and force (N)).

6.3 Case study 1: The squat

Eight subjects of varied gym user level experience each performed five reps of a loaded squat on two separate occasions. Subjects began with their feet placed approximately shoulder width apart and were advised to perform a standard squat as outlined in previous research (Crewther 2011), (Chapter 4 Table 5.3). Each subject was instructed to perform each repetition with as much power as possible and with a two second gap between to ensure velocity was at zero at the beginning of each squat to aid post analysis. The depth of squat was not restricted and varied according to each individual. In total, ten squats for each subject were completed with five performed consecutively in each session. The orientation of the bar and waist mounted accelerometer is identified in Figure 6.3. Vertical movement against gravity is detected in the z axis of the bar mounted accelerometer and the x axis of the waist mounted accelerometer.

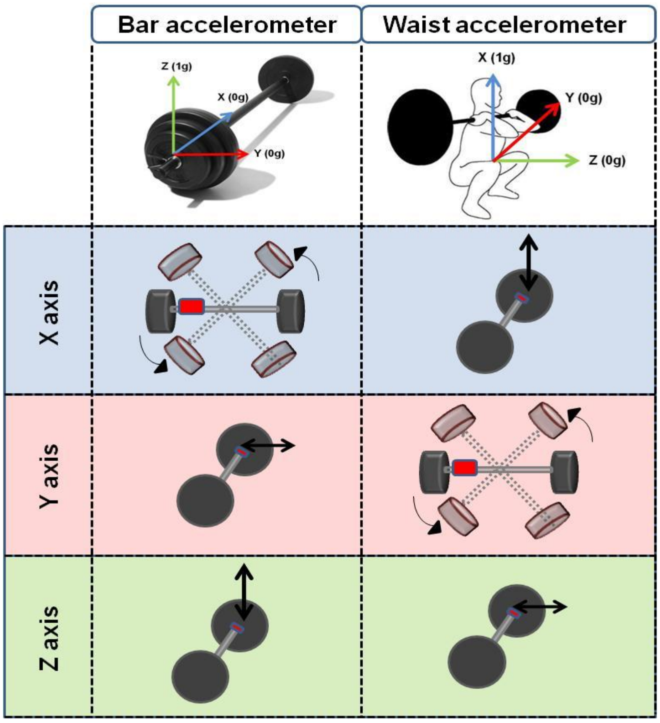


Figure 6.3 Accelerometer orientation

6.3.1 Synchronisation

Synchronisation of the force platform and accelerometer(s) with the video data was achieved by determining the first frame (resolution of 20ms) at which the LED was visible in the camera footage. An example of synchronised squat acceleration profiles derived from the bar mounted accelerometer and video analysis is presented in Figure 6.4. Although the accelerometer and video derived profiles indicate that relative validity (correlation) may exist, differences are apparent between the peak values. Whether the values differ significantly forms a major part of the data analysis in this Chapter.

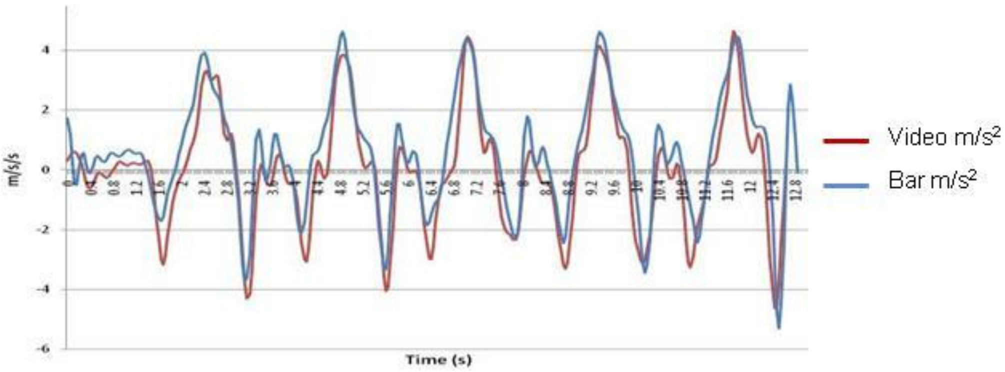


Figure 6.4 Example synchronisation of video and bar accelerometer acceleration profiles

6.3.2 Rep separation

Integration to determine velocity is a cumulative process when using a force platform, any fixed offset in the original data will integrate to a linear variation, either positive or negative depending on the sign of the original offset. To overcome this problem, each rep was analysed individually. The synchronised reps were separated according to when the video displacement returned to the approximate original position. As acceleration is a function of force and mass and the mass remained constant, the acceleration data from the accelerometer exhibited a similar trace to the forceplate GRF and therefore provided the same cut off points for each rep.

The synchronisation of the original data and identification of each rep using the video displacement is presented in Figure 6.5. It is clear that the pattern is repetitive, however, not all subjects paused for two seconds between each rep indicated as a fluctuation of the GRF and accelerometer during the pause. Although this can reduce the accuracy of the peak and mean force, power, acceleration and velocity values determined by integration, it does not impact the ability to investigate relative validity as each system experiences the same fluctuation. Furthermore, in a normal gym environment, restricting the time between each rep may reduce the ability of people to train at higher loads where holding the load between reps is an added strain. Minimising the disruption to a normal resistance training session is a key aspect of performance analysis methods.

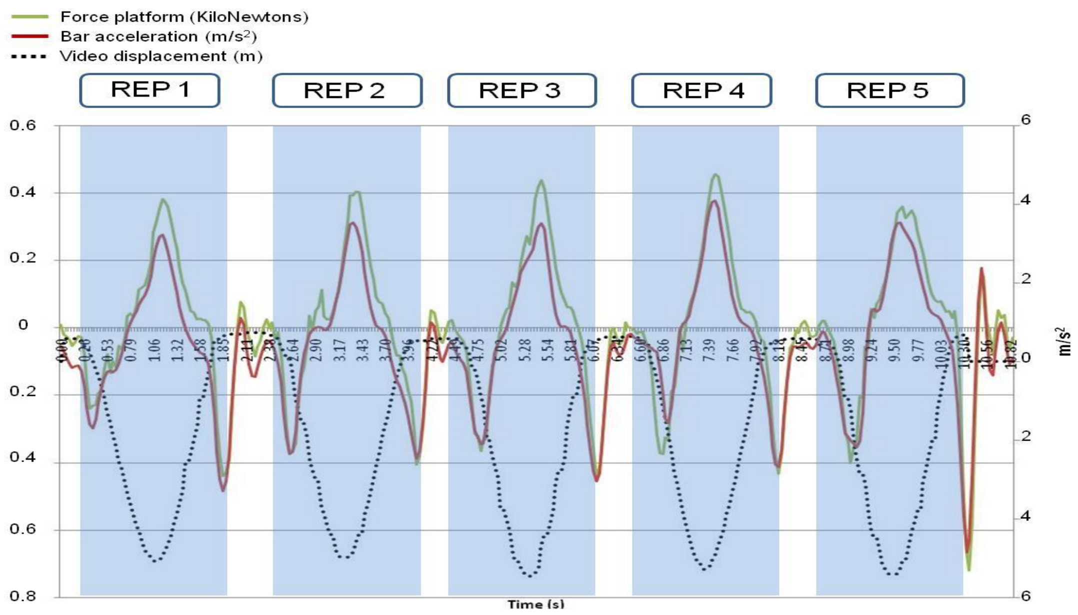


Figure 6.5 Identification of each rep using video displacement

6.3.3 Rep analysis

The following variables were derived from the video, force platform, bar and waist mounted accelerometer for each squat:

- Peak acceleration (PA)
- Peak force (PF)
- Peak velocity (PV)
- Squat depth (SD)

- Time to PA (TTPA)
- Time to PF (TTPF)
- Time to PV (TTPV)
- Time to the end of the eccentric phase (TTEOEP)

6.3.3.1 Calculation of power

The power was calculated using two methods to identify whether one method was less prone to error or misinterpretation than the other:

1. Excluding the total system weight when calculating force (i.e. excluding the body and bar mass) and multiplying by the velocity.
2. Including the total system weight when calculating force (i.e. including the body and bar mass) and multiplying by the velocity.

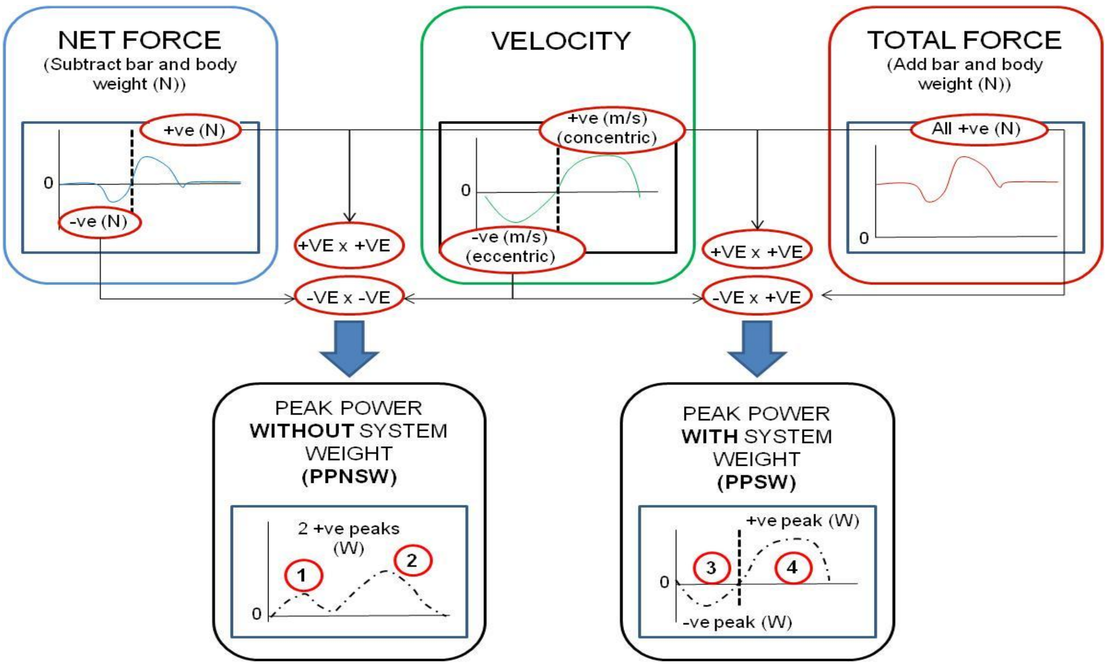


Figure 6.6 Including and excluding the system weight when calculating power

The different calculation methods and the effect on the resultant power profile is illustrated in Figure 6.6. Calculating power without the system weight (using the net force (PPNSW)) reduces the power values. Using the net force causes the force profile to fluctuate around zero, therefore, as the subject enters the eccentric phase, negative force values are derived. When multiplied by the negative eccentric phase of the velocity profile, a positive peak in power occurs (1). In some cases (when high velocity is reached during the eccentric phase) the first peak may be greater than the second positive peak (2), this would have a great impact on the design of an automatic real time monitoring system that relied upon detecting the highest peak in the PPNSW profile. Inaccurate identification of the peak power value and the time at which it occurred is possible. True power lies in the concentric phase where work is being done against gravity, therefore, the application of this method to a real time monitoring system is reliant upon being able to distinguish between the eccentric and concentric peak.

Alternatively, including the system weight in the power calculation (PPSW) causes the same reduction in force but the values are not centred about zero. Therefore, negative force values do not occur. This has a significant impact on the power profile as the negative and positive phases present in the velocity profile influence the power profile. Therefore the eccentric phase remains negative (3) and the concentric phase positive (4). To determine whether the different power profiles affect the absolute and relative validity between video, force platform and accelerometer analysis, the following variables were included in the rep analysis:

- Peak power excluding system weight (PPNSW)
- Peak power including system weight (PPSW)
- Time to PPNSW (TTPPNSW)
- Time to PPSW (TTPPSW)

6.3.4 Results

An example profile derived from the video, force platform and each accelerometer for each performance variable is presented. Whether significant difference exists between the video-force platform, video-bar mounted accelerometer and video-waist mounted accelerometer is determined using the performance variable mean, standard deviation (SD) and standard error between means (SEM). Each is listed in a corresponding performance variable table. A significance value (sig value) less than 2 indicates that no significant difference exists between the compared means. The difference between the video and force platform and video and accelerometers was also calculated for each squat and the mean derived. The mean percentage difference is listed to quantify the difference in relation to the original value derived from the video allowing for comparison between different parameters (such as comparing acceleration (m/s^2) and force (N)).

6.3.4.1 Peak acceleration

Example acceleration profiles derived from the video, force platform, bar and waist mounted accelerometers for one squat are presented in Figure 6.7. Although a similar trace is apparent for each measurement system, the peak values differ. Whether this difference is significant is dependent upon the mean peak acceleration derived for each system and standard error between the means. The mean peak acceleration and error bars (at a 95% confidence interval) for each system are presented in Figure 6.8, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.1. The results indicate that greatest difference exists between the video and force platform (SEM (-0.42 ± 0.25 m/s^2) and sig value (-1.64)). However, the sig value suggests that this difference is not significant (it is less than 2). As previously explained in Chapter 5, the video and accelerometers monitor the kinematics of the bar and body separately whilst the force platform measures movement of the whole body and bar (system mass). Therefore, it is expected that the force platform and video will exhibit the largest difference. The bar and waist mounted accelerometer results indicate high correlation with the mean peak acceleration derived from the video (SEM (-0.21 ± 0.25 m/s^2), sig value (-0.81) and SEM (-0.16 ± 0.25 m/s^2), sig value (-0.65) respectively)). The waist mounted accelerometer has the highest correlation with the video derived data and no significant difference exists between the video derived mean peak acceleration and subsequent methods.

The percentage difference between peak acceleration derived from the video and remaining systems (force platform and accelerometers) was calculated for each squat. The mean percentage difference is listed in Table 6.1. The results support the sig values, the waist mounted accelerometer exhibits the lowest mean percentage difference (-5.0 ± 1.2%), the bar mounted accelerometer (-6.6 ± 1.4%) and the force platform the highest percentage difference (-9.6 ± 1.4 %). Each system underestimates the mean peak acceleration when compared to the video derived values, however, this underestimation is not significant.

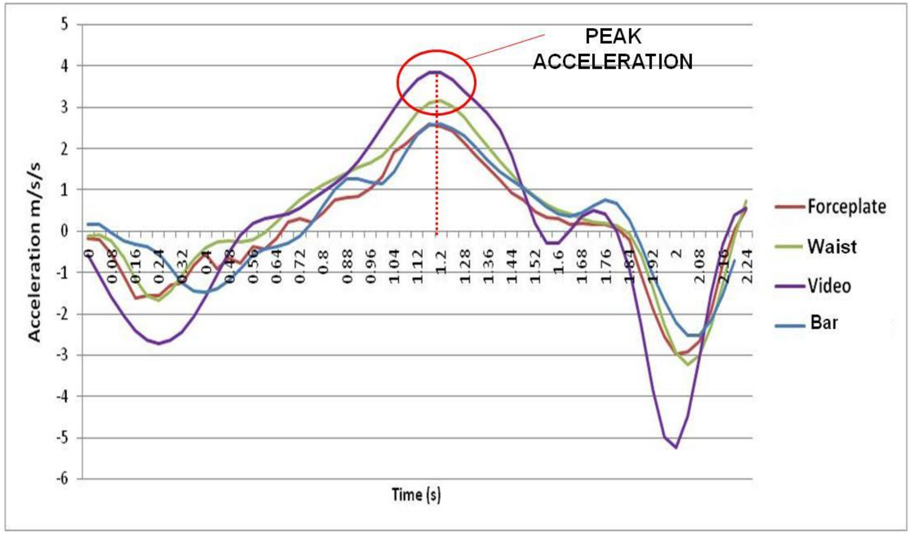


Figure 6.7 Example video, force platform and accelerometer derived acceleration profiles for one squat

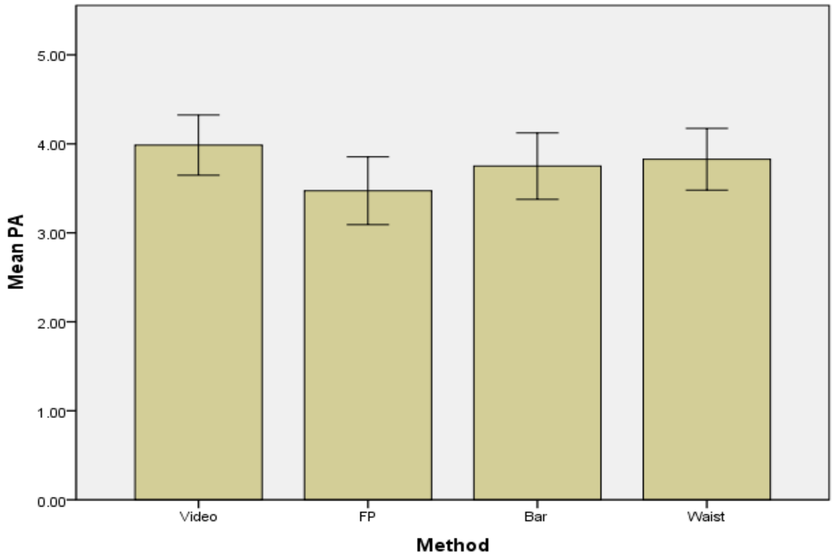


Figure 6.8 Mean peak acceleration and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (m/s^2)	3.98 ± 0.17	3.57 ± 0.19	3.78 ± 0.19	3.83 ± 0.18
Std Deviation	1.52	1.67	1.68	1.56
Std Error between means (m/s^2)	N/A	-0.42 ± 0.25	-0.21 ± 0.25	-0.16 ± 0.25
Sig. Value	N/A	-1.64	-0.81	-0.65
Mean % difference	N/A	-9.6 ± 1.4 %	-6.6 ± 1.4%	-5.0 ± 1.2%

Table 6.1 Statistical analysis of the acceleration results derived from the video, force platform and accelerometers to determine whether significant difference exists.

6.3.4.2 Peak force

The force profiles derived from the video, force platform, bar and waist mounted accelerometers are presented in Figure 6.9. The mean peak force and error bars for each system (presented in Figure 6.10) illustrate the mean, standard deviation, standard error between means and resultant level of significance listed in Table 6.2. As force is a product of mass (a constant) and acceleration, the profiles are similar. The peak acceleration and peak force results are statistically consistent, therefore, once again, the greatest difference exists between the video and force platform (SEM (-76 ± 46 N) and sig value (-1.66)). The sig value suggests that the difference is not significant. The bar and waist mounted accelerometer results indicate high correlation with the mean peak force derived from the video (SEM (-43 ± 46 N), sig value (-0.93) and SEM (-24 ± 44 N), sig value (-0.53) respectively)). Therefore, no significant difference exists between the video derived peak force mean and subsequent methods. The waist mounted accelerometer has the highest correlation with the video derived data.

The mean percentage difference is listed in Table 6.2, the results support the sig values. The waist mounted accelerometer exhibits the lowest mean percentage difference (-5.4 ± 1.3%), the bar mounted accelerometer (-7.47 ± 1.8%) and the force platform the highest percentage difference (-11.6 ± 1.8%). Each system underestimates the mean peak force when compared to the video derived values, however, this difference is not significant. Once again, the difference between the force platform and video is attributed to the force platform measuring the system mass (bar and body) whilst the video analysis measured the bar and body separately. Although force platform technology would provide the most accurate peak force data, it is accelerometer performance that is of most interest. Directly comparing force platform and accelerometer derived data would produce inaccurate results as the accelerometers do not measure acceleration of the system mass.

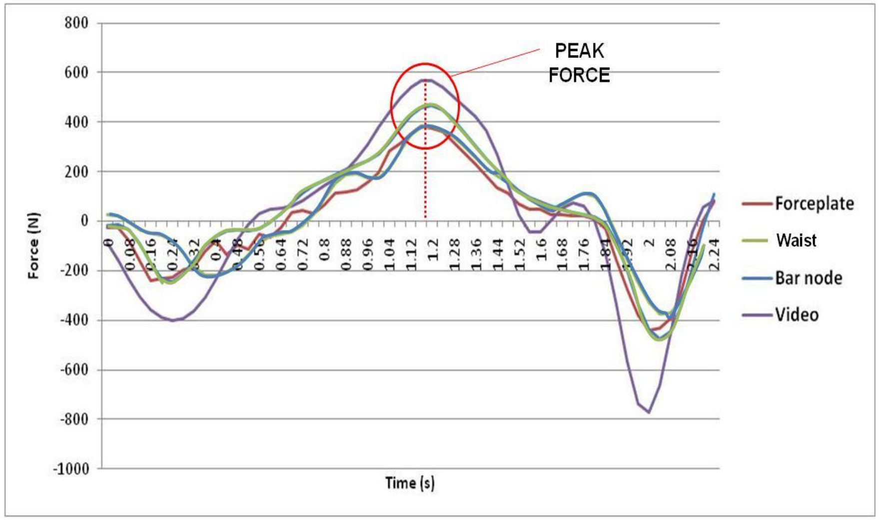


Figure 6.9 Example video, force platform and accelerometer derived force profiles for one squat.

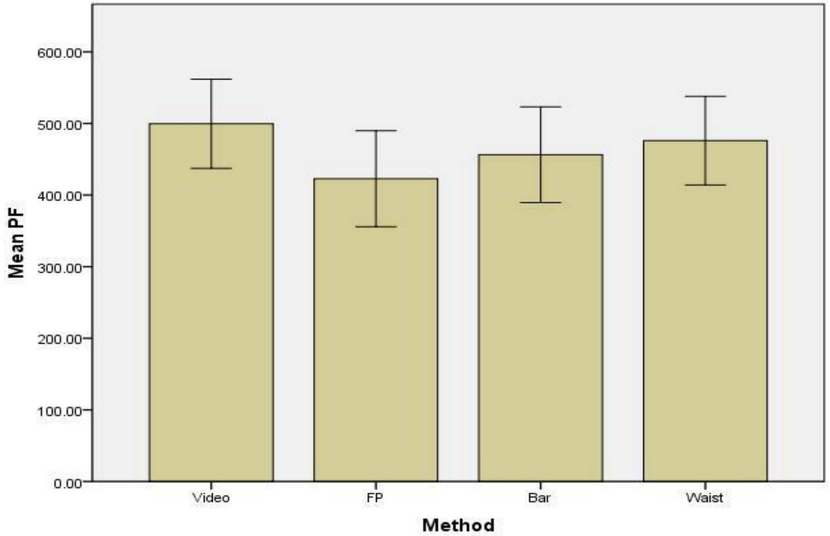


Figure 6.10 Mean peak force and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (N)	499 ± 31	422 ± 34	456 ± 34	476 ± 31
Std Deviation	280	301	300	278
Std Error between means (N)	N/A	-76 ± 46	-43 ± 46	-24 ± 44
Sig. value	N/A	-1.66	-0.93	-0.53
Mean % difference	N/A	-11.6 ± 1.8%	-7.47 ± 1.8%	-5.4 ± 1.3%

Table 6.2 Statistical analysis of the force results derived from the video, force platform and accelerometers to determine whether significant difference exists

6.3.4.3 Peak velocity

An example of the velocity profiles derived from the video, force platform, bar and waist mounted accelerometers for one squat are presented Figure 6.11. The mean peak velocity and error bars (at a 95% confidence interval) for each system are presented in Figure 6.12, whilst the mean, standard deviation, standard error between means and level of significance are listed in Table 6.3. The results indicate that greatest difference exists between the video and force platform (SEM (-0.11 ± 0.05m/s) and sig value (-1.98)). However, the sig value (although higher than the mean peak acceleration and mean peak force) suggests that this difference is not significant. The bar and waist mounted accelerometer results indicate higher correlation with the mean peak velocity derived from the video (SEM (-0.06 ± 0.05 m/s), sig value (-1.07) and SEM (0.04 ± 0.05 m/s), sig value (0.76) respectively)).

Similarly to the mean peak acceleration and mean peak force results, the waist mounted accelerometer has the highest correlation with the video derived data. However, in contrast to the previous results, the velocity is overestimated. This may affect other calculations (such as power) that are derived from velocity as this overestimation will be further amplified throughout the profile. The sig values suggest that the difference between the video and force platform (-1.66), video and bar and waist mounted accelerometers (-0.93 and -0.53 respectively) derived mean velocity is not significant. However, less correlation is indicated by an increase in the sig value for each method. The force platform, bar mounted accelerometer and waist mounted accelerometer sig value increased by 0.34, 0.26 and 0.11, respectively when compared to the mean peak acceleration sig values. This increased difference can be attributed the error accumulated due to the integration process required to derive velocity from acceleration. The mean percentage difference between the video-force platform, video-bar mounted accelerometer and video-waist mounted accelerometer is listed in Table 6.3. The results support the sig values, the waist mounted accelerometer exhibits the lowest mean percentage difference (4.3 ± 1.4%), the bar mounted accelerometer (-7.9 ± 2.7%) and the force platform the highest percentage difference (-10.1 ± 1.7%).

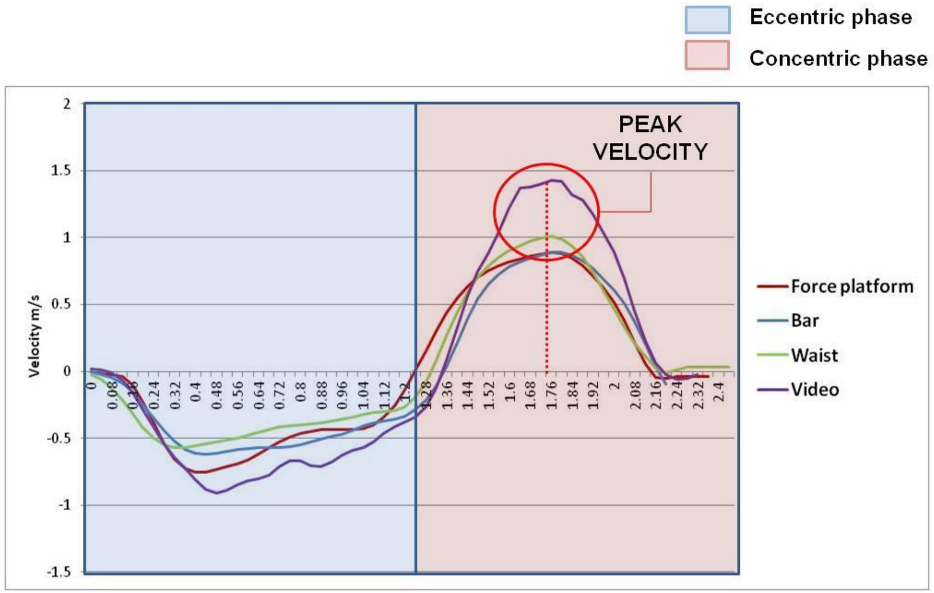


Figure 6.11 Example video, force platform and accelerometer derived velocity profiles for one squat.

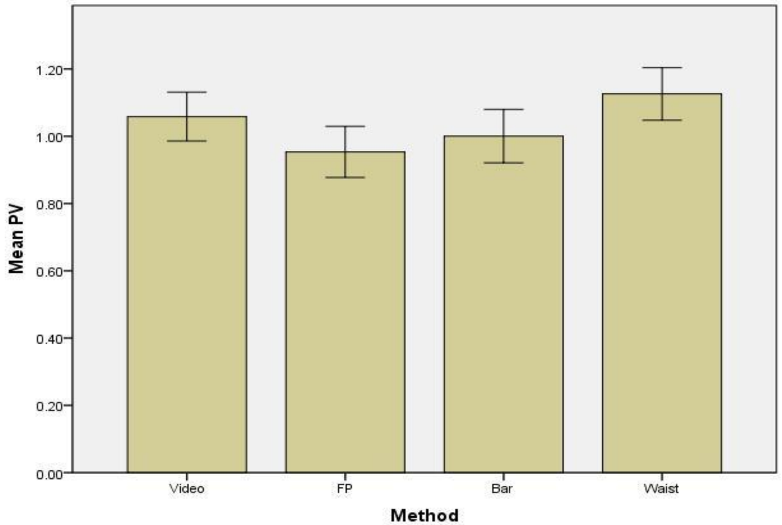


Figure 6.12 Mean peak velocity and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (m/s)	1.06 ± 0.04	0.95 ± 0.04	1.00 ± 0.04	1.10 ± 0.04
Std Deviation	0.33	0.34	0.36	0.33
Std Error between means (m/s)	N/A	-0.11 ± 0.05	-0.06 ± 0.05	0.04 ± 0.05
Sig. value	N/A	-1.98	-1.07	0.76
Mean % difference	N/A	-10.1 ± 1.7%	-7.9 ± 2.7%	4.3 ± 1.4%

Table 6.3 Statistical analysis of the velocity results derived from the video, force platform and accelerometers to determine whether significant difference exists.

6.3.4.4 Squat depth

An example of the eccentric displacement profiles derived from the video, force platform, bar and waist mounted accelerometers for one squat is presented Figure 6.13. The mean peak displacement and error bars (at a 95% confidence interval) for each system are presented in Figure 6.14, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.4.

The results indicate that the maximum squat depth derived from each method is significantly different from the video derived displacement (force platform sig value = -3.05, bar accelerometer sig value = -2.38, waist accelerometer sig value = 2.73). Calculation of the displacement requires double integration of the acceleration data, therefore, it is expected that the sig values increase further to show less correlation than the mean peak velocity results. The error is propagated from the velocity using each method, therefore, the greatest difference exists between the video and force platform (SEM (-0.08 ± 0.02 m). This difference is closely followed by both accelerometers (bar mounted SEM = -0.07 ± 0.03 m and waist mounted SEM = 0.07 ± 0.03).

The waist mounted accelerometer peak velocity results indicate an overestimation of velocity, it would therefore be expected that the squat depth (derived from the velocity) would also reflect an overestimation of the squat depth as the error is propagated. This is reflected by overestimation of the squat depth when derived from the waist mounted accelerometer (SEM 0.07 ± 0.03 m) in comparison to the video displacement data. The mean percentage differences are listed in Table 6.4. The waist mounted accelerometer exhibits the lowest mean percentage difference (13.2 ± 3.1%), the bar mounted accelerometer (-14.0 ± 3.3%) and the force platform the highest percentage difference (-17.1 ± 1.3%). Calculating the squat depth using double integration of the acceleration profile increases the error and resultant difference between the results derived from the video and each system. Therefore, the sig values indicate that significant difference exists between the video and each system (force platform, bar mounted and waist mounted accelerometer).

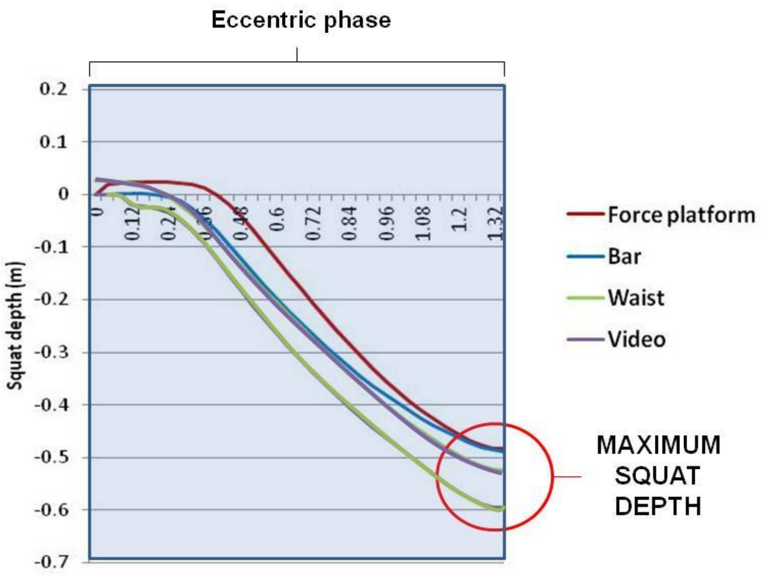


Figure 6.14 Example video, force platform and accelerometer derived squat depth for one squat.

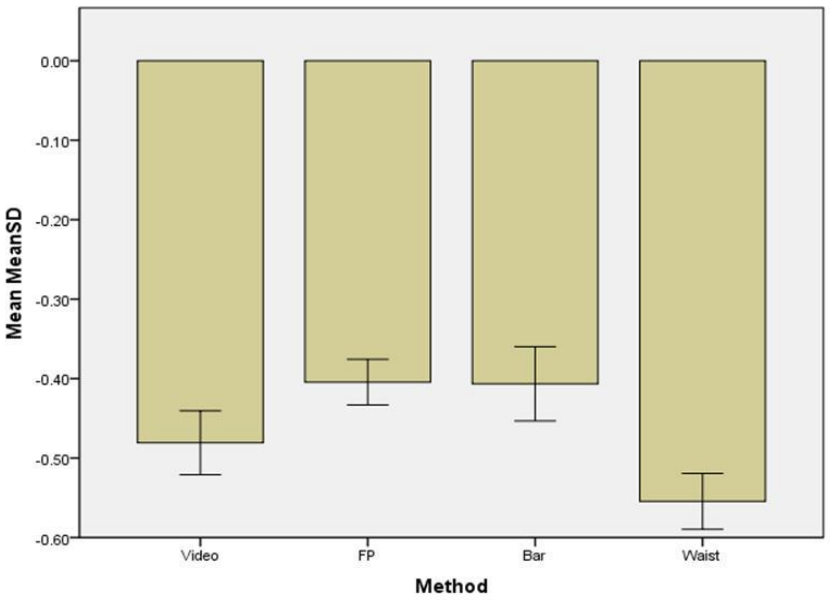


Figure 6.13 Mean peak squat depth and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (m)	-0.48 ± 0.02	-0.40 ± 0.01	-0.41 ± 0.02	-0.55 ± 0.02
Std Deviation	0.18	0.13	0.21	0.18
Std Error between means (m)	N/A	-0.08 ± 0.03	-0.07 ± 0.03	0.07 ± 0.03
Sig. value	N/A	-3.05	-2.38	2.73
Mean % difference	N/A	-17.1 ± 1.3%	-14.0 ± 3.3%	13.2 ± 3.1%

Table 6.4 Statistical analysis of the squat depth results derived from the video, force platform and accelerometers to determine whether significant difference exists.

6.3.4.5 Calculating peak power excluding system weight (PPNSW)

The power (excluding system weight) profiles derived from the video, force platform, bar and waist mounted accelerometers are presented in Figure 6.15. The mean difference between each method of analysis and corresponding standard error of the means is presented in Figure 6.16. The results indicate that, on average, the force platform, bar and waist accelerometer each produce lower peak power values when compared to the video values; (force platform = -149 ± 36, bar= -73 ± 42, waist= -60 ± 42). The mean difference for the force platform does not fall within 2 standard errors (2 SE) (sig value (-4.14)), therefore the force platform values are significantly different from the video. However, the bar and waist accelerometer mean differences lie within 2 SE of the video (sig value (-1.75) and (-1.41), respectively). Therefore, significant difference does not exist between the video and accelerometer derived values when calculating peak power without the system weight. The waist mounted accelerometer has the lowest significance value (-1.41), implying that this method of analysis produces results most similar to the video derived results.

The force platform mean percentage difference is the highest (-29.9% ± 4.7%) indicating further that significant difference exists between the force platform and video derived PPNSW results. The bar mounted accelerometer mean percentage difference is -14.6% ± 4.2%, whilst the waist mounted accelerometer has the lowest overall percentage difference mean (-8.5% ± 5.2%). The results indicate that the maximum mean percentage difference for the bar mounted accelerometer is less than -19% whilst the maximum mean percentage difference for the waist mounted accelerometer is less than 14%. The force platform maximum mean difference is much higher (34.6%). The mean peak force and mean peak velocity derived from the force platform both exhibited the highest percentage difference and highest sig value when compared to the accelerometers. As power is a product of force and velocity, the underestimation identified in both variables using the force platform is propagated when calculating power. Therefore, the high sig value and mean power percentage difference can be attributed to the mean force difference (-76 ± 46 (N)) and mean velocity difference (-0.11 ± 0.05 (m/s)), both of which indicate underestimation of the mean values derived from the video.

6.3.4.6 Peak power including system weight (PPSW)

The power (including system weight) profiles derived from the video, force platform, bar and waist mounted accelerometers are presented in Figure 6.17. The mean difference between each method of analysis and corresponding standard error of the means is presented in Figure 6.18. The overall means are higher when compared to the PPNSW values (due to the inclusion of the system weight when calculating force). The force platform and bar accelerometer again produce lower peak power values when compared to the video values: (force platform SEM = -408 ± 104 and bar SEM = -42 ± 121). However, in contrast to the PPNSW, the waist mounted accelerometer, on average, overestimates the PPSW (SEM 152 ± 123). As discussed previously, this method of power calculation is more affected by the velocity profile than the when the system weight is not included. Therefore, it is suggested that the overestimation present in the mean peak velocity values derived from the waist mounted accelerometer are propagated by this method of power calculation.

Although the force platform mean difference and resultant sig values are lower than those derived from the PPNSW (excluding system weight), significant difference still exists (sig value (-3.91)). The mean difference for the force platform does not fall within 2 standard errors (SE), therefore the force platform values are significantly different from the video. However, the bar and waist accelerometer mean differences lie within 2 SE of the video (sig values (-0.35) and (1.26) respectively). Therefore, significant difference does not exist between the video and accelerometer derived values when calculating peak power without the system weight. In contrast to the other variables, the bar mounted accelerometer has the lowest significance value (-0.35).

The force platform mean percentage difference is the highest (-24.0 ± 3.7%) indicating further that significant difference exists between the force platform and video derived PPNSW results. The waist mounted accelerometer mean percentage difference is (15.3 ± 4.8%), whilst the bar mounted accelerometer has the lowest overall mean percentage difference (-0.98 ± 5.1%). The results indicate that the maximum mean percentage difference for the bar mounted accelerometer is less than -6.1% whilst the maximum mean percentage difference for the waist mounted accelerometer is less than 19%. The force platform maximum mean difference is much higher (27.7%). The high sig value and mean percentage difference derived from the force platform can once again be attributed to the previously identified mean peak force difference and mean peak velocity difference. The waist mounted accelerometer results do not show the highest correlation with the video derived data as with the previous variables. It is suggested that the overestimation present in the mean peak velocity has been amplified further using the PPSW calculation.

The calculation of power using both methods resulted in the lowest correlation with the video derived data for each method. As previously stated, this can be attributed to deriving power from two other variables, any error is propagated when multiplied. Histograms were created to investigate the spread of percentage difference when calculating the peak power without the system weight (PPNSW) and with the system weight (PPSW) presented in Figures 6.19 and 6.20. The differences are derived for the force platform (a), bar mounted accelerometer (b) and waist mounted accelerometer (c). The results indicate that each method has a large range of percentage difference, therefore the differences present in the derived force and velocity profiles are amplified further when calculating power with and without the system weight. These results suggest that highest correlation with the video derived data is achieved using the bar mounted accelerometer and the PPSW method (including the system weight).

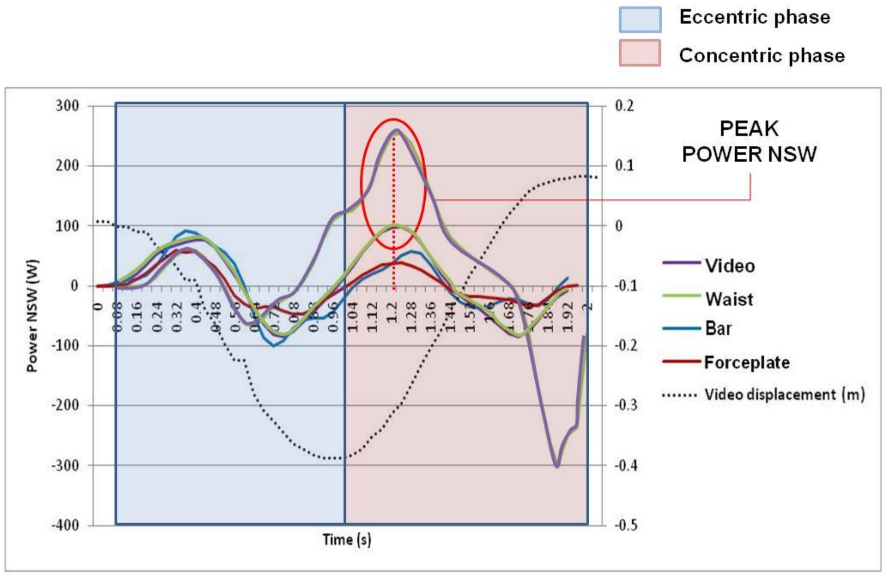


Figure 6.16 Example video, force platform and accelerometer derived PPNSW for one squat.

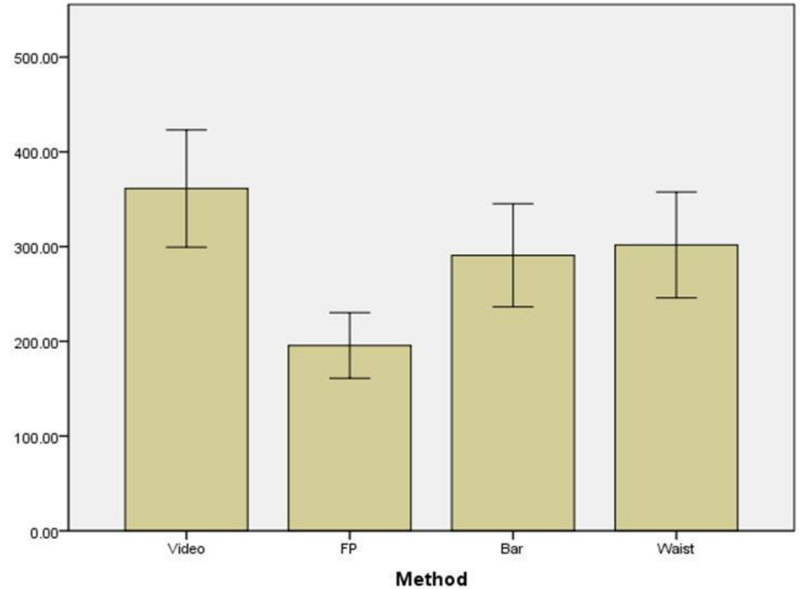


Figure 6.15 Mean peak PPNSW and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (W)	361 ± 31	211 ± 18	288 ± 27	302 ± 28
Std Deviation	278	162	245	251
Std Error between means (W)	N/A	-149 ± 36	-73 ± 42	-60 ± 42
Sig. Value	N/A	-4.14	-1.75	-1.41
Mean % difference	N/A	-29.9 ± 4.7%	-14.6 ± 4.2%	-8.5 ± 5.2%

Table 6.5 Statistical analysis of the PPNSW results derived from the video, force platform and accelerometers to determine whether significant difference exists.

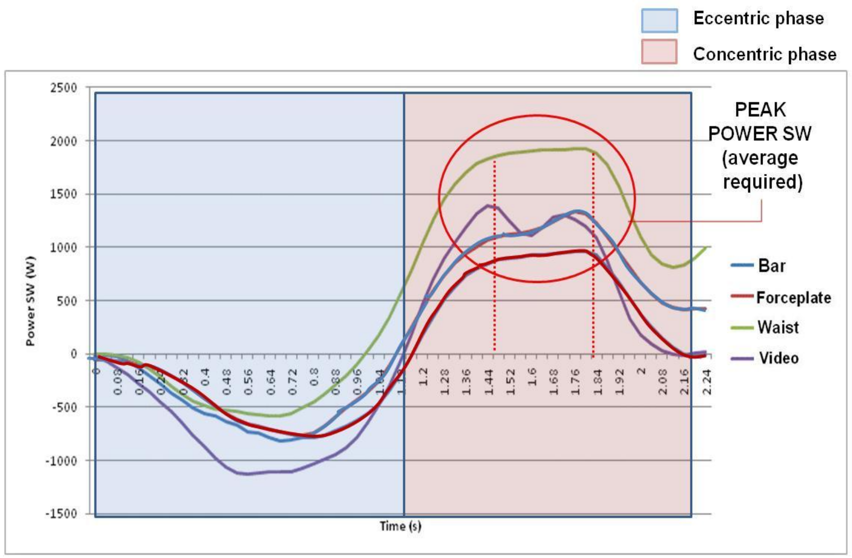


Figure 6.17 Example video, force platform and accelerometer derived PPSW for one squat.

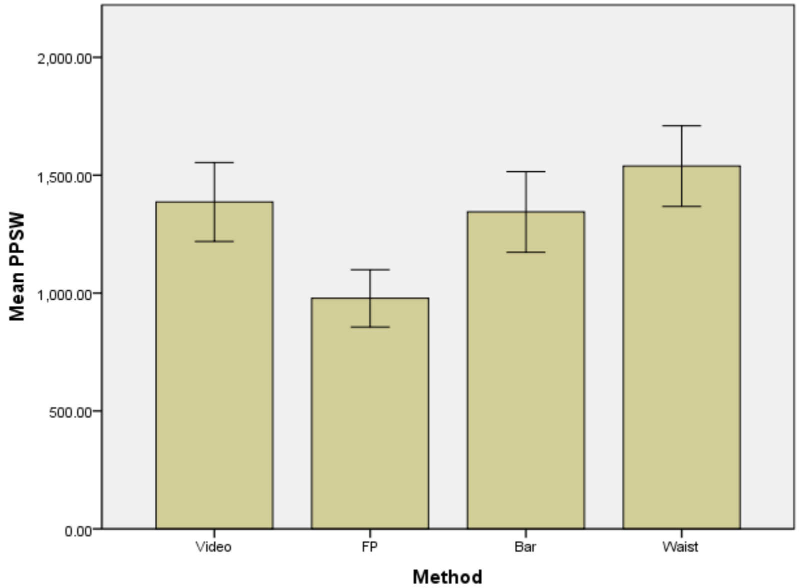


Figure 6.18 Mean peak PPSW and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (W)	1386 ± 83	978 ± 61	1344 ± 86	1539 ± 86
Std Deviation	750	545	767	769
Std Error between means (W)	N/A	-408 ± 104	42 ± 121	152 ± 123
Sig. Value	N/A	-3.91	-0.35	1.26
Mean % difference	N/A	-24.0 ± 3.7%	0.98 ± 5.1%	15.3 ± 4.8%

Table 6.6 Statistical analysis of the PPSW results derived from the video, force platform and accelerometers to determine whether significant difference exists.

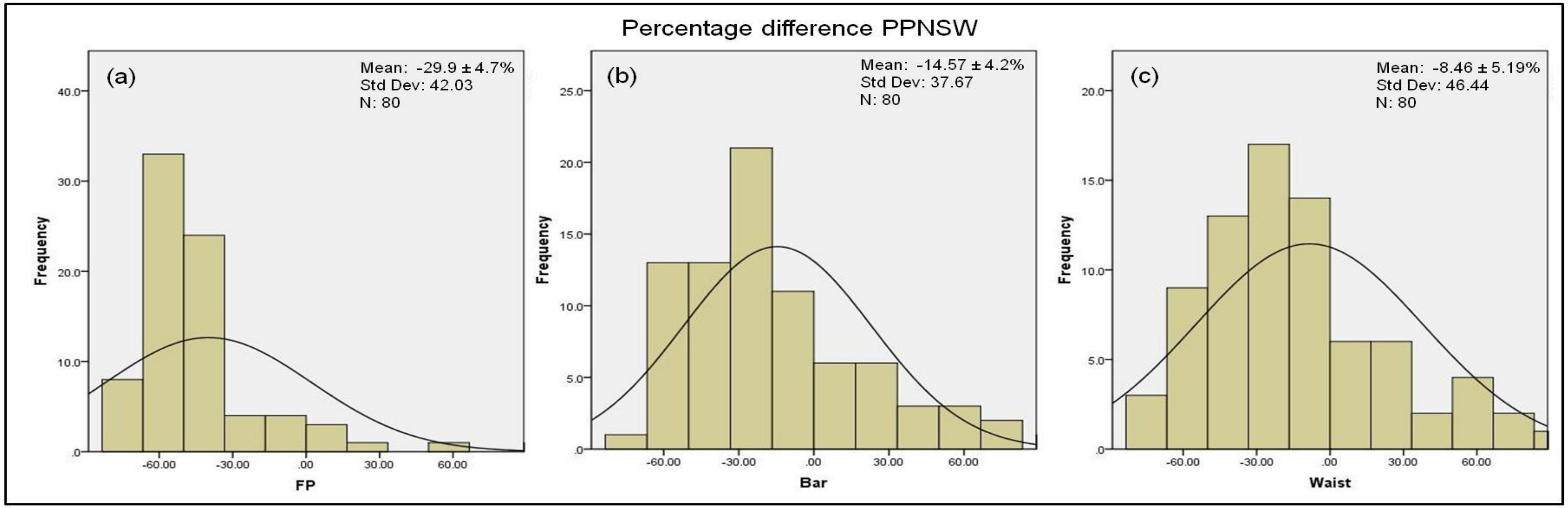


Figure 6.20 The mean percentage PPNSW difference between video and forceplate, video and bar mounted accelerometer and video and waist mounted accelerometer.

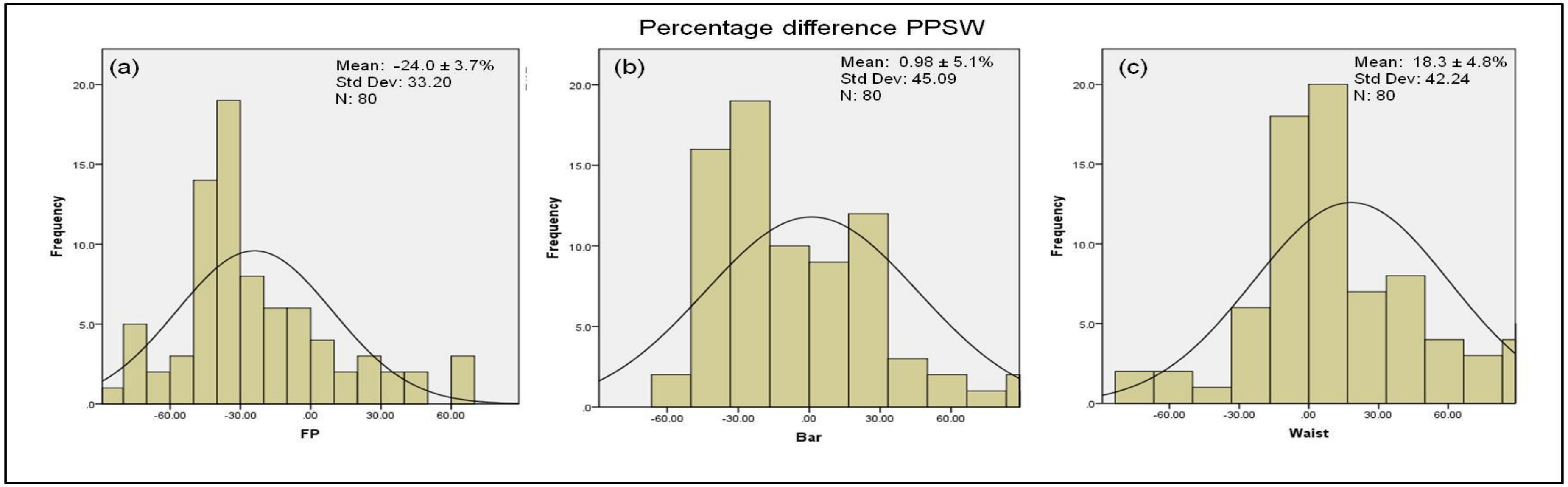


Figure 6.19 The mean percentage PPSW difference between video and forceplate, video and bar mounted accelerometer and video and waist mounted accelerometer.

6.3.4.7 Relative validity: Time to peak values

Determining the mean difference between the video, force platform, bar mounted and waist mounted accelerometers for the identified variables provides an understanding of the absolute validity between the methods (whether significant difference exists between the mean values). Determining whether the peak values occur at the same time when using each method provides an understanding of the relative validity between each method. The time to peak acceleration, force, velocity, end of the eccentric phase (maximum squat depth) and power with and without the system weight was calculated using each method. The results are discussed in the following section.

6.3.4.8 Time to peak acceleration

An example of the identification of the time to peak acceleration derived from the video, force platform, bar and waist mounted accelerometers for one squat is presented Figure 6.21. The mean time to peak acceleration and error bars (at a 95% confidence interval) for each system are presented in Figure 6.22, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.7.

The results indicate that there is high correlation between all three methods when compared to the video results. Each system exhibits low mean differences and sig values. Both the force platform and bar mounted accelerometer have the highest correlation with the video (SEM (0.006 ± 0.04 s), sig value (0.14) and SEM (0.006 ± 0.04 s), sig value (0.14), respectively). The waist mounted accelerometer has slightly less correlation (SEM (0.014 ± 0.04 s), sig value (0.30)), however, the difference between the video and each method is not significant. The mean percentage differences indicate that the bar mounted accelerometer exhibits the lowest percentage difference (0.6 ± 0.7%), the force platform and waist mounted accelerometer have the same mean percentage difference (1.0 ± 0.9%). Each method is within ± 2% of the time to peak value derived from the video, therefore, high relative validity exists between the video and subsequent systems.

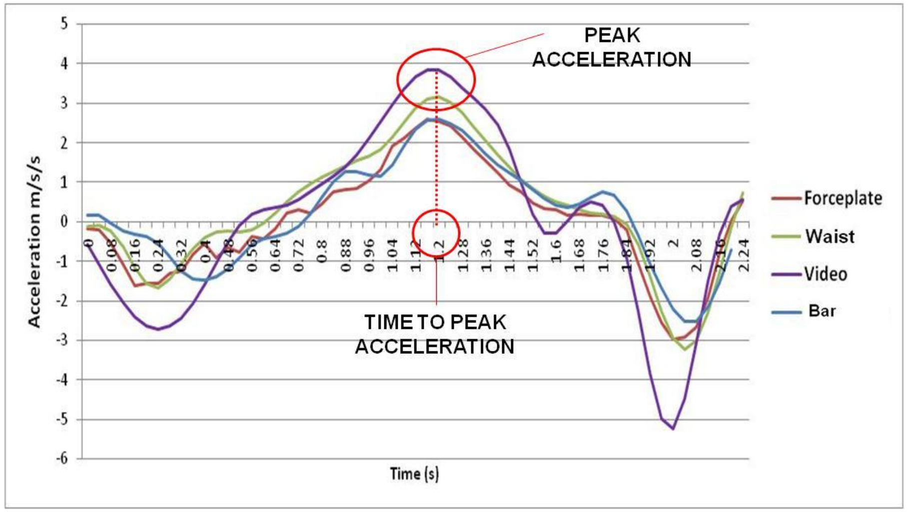


Figure 6.22 Example video, force platform and accelerometer derived TTPA for one squat.

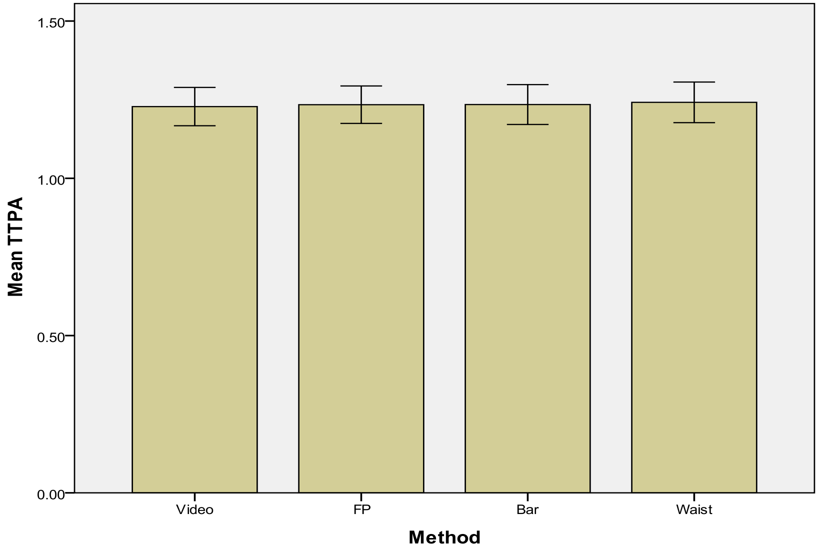


Figure 6.21 Mean peak TTPA and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (s)	1.23 ± 0.03	1.23 ± 0.03	1.23 ± 0.03	1.24 ± 0.03
Std Deviation	0.27	0.27	0.28	0.29
Std Error between means (s)	N/A	0.006 ± 0.04	0.006 ± 0.04	0.014 ± 0.04
Sig. value	N/A	0.14	0.14	0.30
Mean % difference	N/A	1.0 % ± 0.9%	0.6 ± 0.7%	1.0 ± 0.9%

Table 6.8 Statistical analysis of the TTPA results derived from the video, force platform and accelerometers to determine whether significant difference exists.

6.3.4.9 Time to peak force

An example of the identification of the time to peak force derived from the video, force platform, bar and waist mounted accelerometers for one squat is presented Figure 6.23. The mean time to peak force and error bars (at a 95% confidence interval) for each system are presented in Figure 6.24, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.8.

The results support those derived from the acceleration profiles as the peak force inevitably occurs when peak acceleration occurs (as mass is constant). Therefore, high correlation exists between all three methods when compared to the video results with each method exhibiting low mean differences and sig values (force platform = SEM (0.009 ± 0.04 s), sig value (0.21), bar mounted accelerometer = SEM (0.010 ± 0.04 s), sig value (0.21) and waist mounted accelerometer = SEM (0.017 ± 0.04 s), sig value (0.37)). The difference between the video and each method is therefore not significant. The mean percentage differences indicate that the bar mounted accelerometer exhibits the lowest percentage difference (0.9 ± 0.8%), whilst the force platform (1.3 ± 0.9%) and waist mounted accelerometer (1.3 ± 1%) also exhibit low percentage differences. Each method is within ± 2.3% of the time to peak value derived from the video, therefore, high relative validity exists between the video and subsequent systems.

6.3.4.10 Time to peak velocity

An example of the identification of the time to peak velocity derived from the video, force platform, bar and waist mounted accelerometers for one squat is presented Figure 6.25. The mean time to peak velocity and error bars (at a 95% confidence interval) for each system are presented in Figure 6.26, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.9. The results reflect the same increase in error when using the velocity profile as identified when comparing the peak velocity (see Section 6.3.4.3). The time to peak velocity results exhibit an increase in mean difference and sig value when using the force platform (SEM (0.06 ± 0.03 s), sig value (1.84)), bar mounted accelerometer (SEM (0.06 ± 0.03 s), sig value (1.60)) and waist mounted accelerometer (SEM (0.03 ± 0.04 s), sig value (0.87)). These sig values are supported further by the percentage differences which indicate that the highest percentage difference exists between the video and force platform derived time to peak velocity (4.1 ± 0.6%). The least percentage difference exists between the video and waist mounted accelerometer (1.9 ± 0.5%), whilst the bar mounted accelerometer results lie within the waist mounted accelerometer and force platform mean percentage difference ranges (3.6 ± 0.6%). Despite the increased mean difference, sig value and percentage difference for each method, the difference is not significant.

6.3.4.11 Time to the end of the eccentric phase (maximum squat depth)

An example of the identification of the time to the end of the eccentric phase (TTEOEP) derived from the video, force platform, bar and waist mounted accelerometers for one squat is presented Figure 6.27. The mean TTEOEP and error bars (at a 95% confidence interval) for each system are presented in Figure 6.28, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.10. The end of the eccentric phase was determined from the force platform and accelerometer data using the point at which the velocity crossed zero in comparison to the digitised point at which the subject reached maximum squat depth (the end of the eccentric phase). In contrast to the squat depth peak value results, the time to peak results do not show significant difference. Although the peak values may differ, the force platform (SEM (0.03 ± 0.04 s), sig value (0.75)), bar mounted accelerometer (SEM (-0.04 ± 0.04 s), sig value (-1.13)) and waist mounted accelerometer (SEM (-0.02 ± 0.04 s), sig value (-0.66)), each highly correlate with the video derived results.

The percentage differences indicate that the highest difference exists between the video and force platform derived time to the end of the eccentric phase (2.3 ± 0.6%), with the least percentage difference existing between the video and waist mounted accelerometer (-2.5 ± 0.8%). The bar mounted accelerometer results lie within these ranges (-3.2 ± 1.1%). Overall, the results indicate that despite the high mean difference, sig values and percentage difference produced when calculating the squat depth using each method, the time to the end of the eccentric phase can still be determined. Therefore, high relative validity exists between the video and each system.

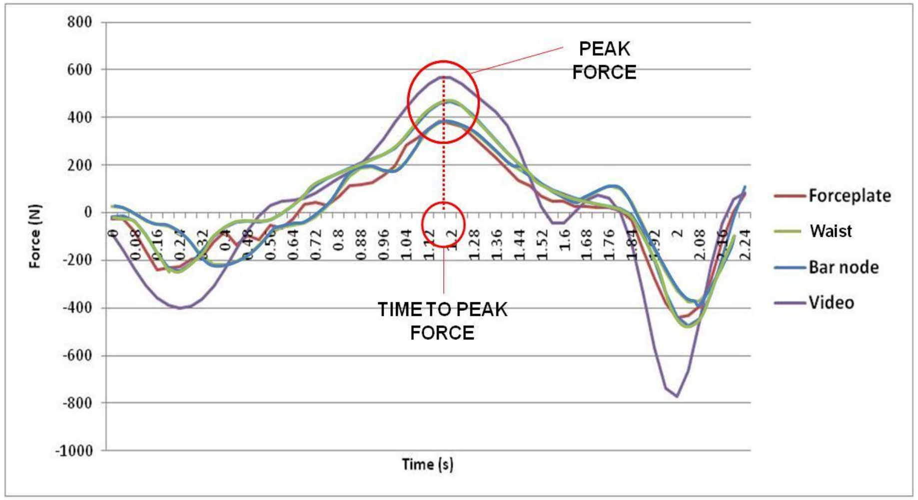


Figure 6.23 Example video, force platform and accelerometer derived TTPF for one squat.

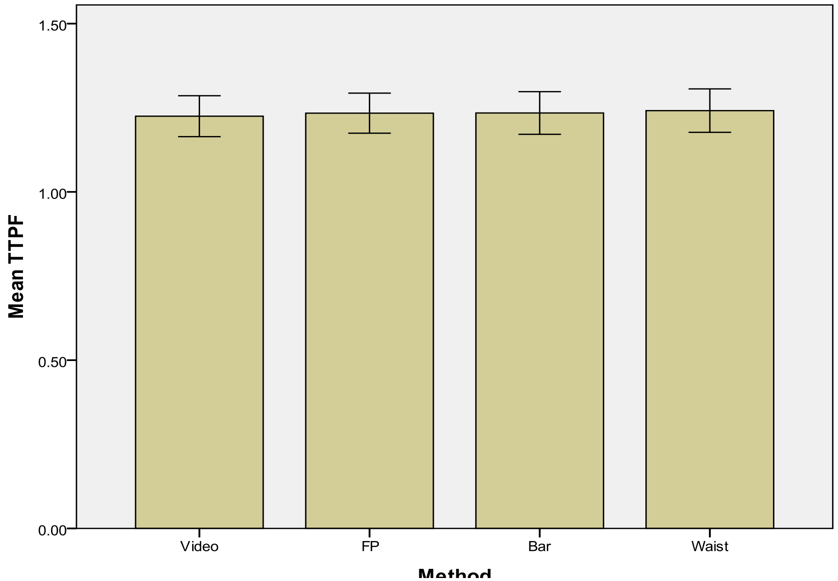


Figure 6.24 Mean peak TTPF and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (s)	1.23 ± 0.03	1.23 ± 0.03	1.23 ± 0.03	1.24 ± 0.03
Std Deviation	0.27	0.27	0.28	0.29
Std Error between means (s)	N/A	0.009 ± 0.04	0.010 ± 0.04	0.017 ± 0.04
Sig. Value	N/A	0.21	0.21	0.37
Mean % difference	N/A	1.3 ± 0.9%	0.9 ± 0.8%	1.3 ± 1%

Table 6.7 Statistical analysis of the TTPF results derived from the video, force platform and accelerometers to determine whether significant difference exists.

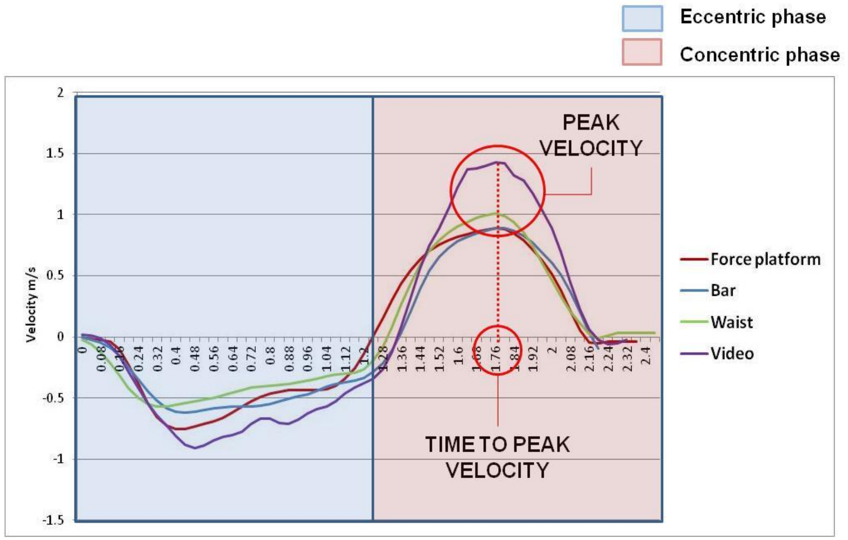


Figure 6.25 Example video, force platform and accelerometer derived TTPV for one squat.

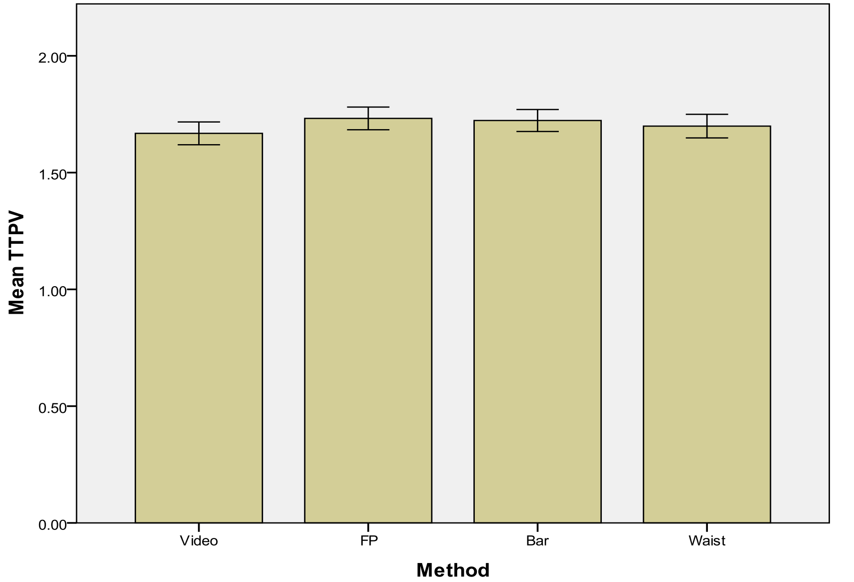


Figure 6.26 Mean peak TTPV and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (s)	1.67 ± 0.02	1.73 ± 0.02	1.72 ± 0.02	1.70 ± 0.03
Std Deviation	0.22	0.22	0.21	0.24
Std Error between means (s)	N/A	0.06 ± 0.03	0.06 ± 0.03	0.03 ± 0.04
Sig. value	N/A	1.84	1.60	0.87
Mean % difference	N/A	4.1 ± 0.6%	3.6 ± 0.6%	1.9 ± 0.5%

Table 6.8 Statistical analysis of the TTPV results derived from the video, force platform and accelerometers to determine whether significant difference exists.

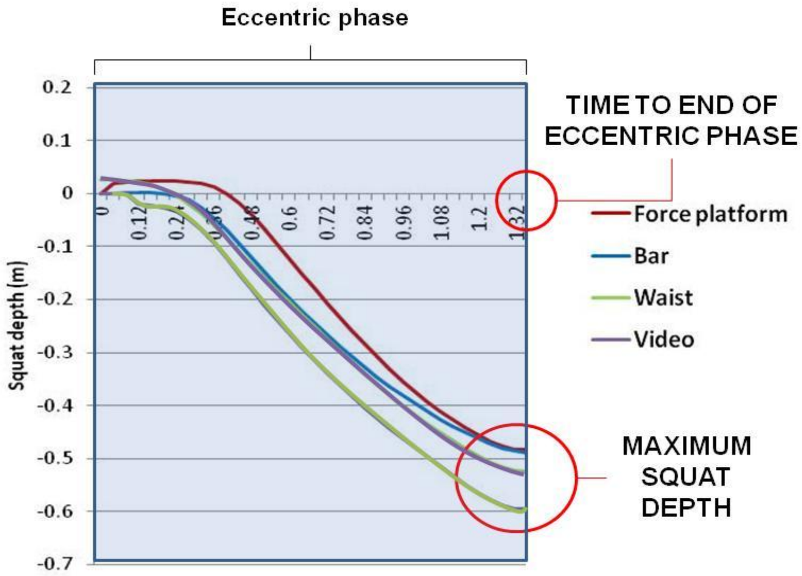


Figure 6.28 Example video, force platform and accelerometer derived TTEOEP for one squat.

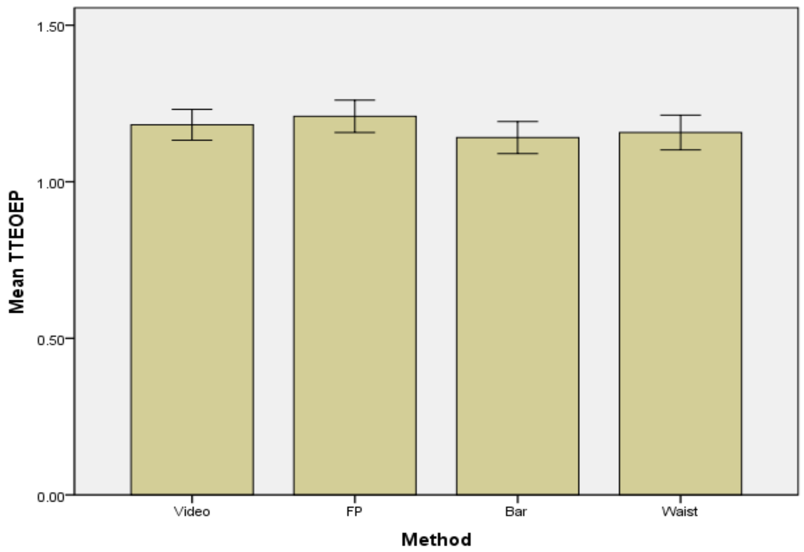


Figure 6.27 Mean peak TTEOEP and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (s)	1.18 ± 0.02	1.21 ± 0.03	1.14 ± 0.03	1.16 ± 0.03
Std Deviation	0.22	0.23	0.23	0.25
Std Error between means (s)	N/A	0.03 ± 0.04	-0.04 ± 0.04	-0.02 ± 0.04
Sig. value	N/A	0.75	-1.13	-0.66
Mean % difference	N/A	2.3 ± 0.6%	-3.2 ± 1.1%	-2.5 ± 0.8%

Table 6.9 Statistical analysis of the TTEOEP results derived from the video, force platform and accelerometers to determine whether significant difference exists.

6.3.4.12 Time to peak power excluding the system weight (TTPPNSW)

An example of the identification of the time to peak power (without the system weight-TTPPNSW) derived from the video, force platform, bar and waist mounted accelerometers for one squat is presented Figure 6.29. The mean TTPPNSW and error bars (at a 95% confidence interval) for each system are presented in Figure 6.30, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.11. Each method overestimates the time at which peak power occurs when compared to the video (force platform (SEM (0.05 ± 0.05 s), sig value (1.19)), bar mounted accelerometer (SEM (0.04 ± 0.04 s), sig value (1.06)) and waist mounted accelerometer (SEM (0.06 ± 0.04s), sig value (1.55)). Although the difference is not significant, the increased error may be attributed to the lower timing errors occurring in the force and velocity profiles. The percentage differences indicate that the highest difference exists between the video and waist mounted accelerometer derived TTPPNSW (4.2 ± 1.2%).). The least percentage difference exists between the video and bar mounted accelerometer (3.0 ± 1.4%) and the force platform results lie within this range (3.9 ± 2.2%).

6.3.4.13 Time to peak power including the system weight (TTPPSW)

An example of the identification of the time to peak power (with the system weight-TTPPSW) derived from the video, force platform, bar and waist mounted accelerometers for one squat is presented Figure 6.31. The mean TTPPSW and error bars (at a 95% confidence interval) for each system are presented in Figure 6.32, the mean, standard deviation, standard error between means and level of significance is listed in Table 6.12. Similar to the TTPPNSW, each method overestimates the time at which peak power occurs when compared to the video (force platform (SEM (0.09 ± 0.03 s), sig value (2.83)), bar mounted accelerometer (SEM (0.06 ± 0.03 s), sig value (1.68)) and waist mounted accelerometer (SEM (0.11 ± 0.04 s), sig value (3.06)). The difference between the force platform and waist mounted accelerometer is also identified as significant (the sig value is higher than 2). The profile generated when including the system weight does not provide a distinct point at which peak power occurs, therefore it is suggested that an average is required to gain an accurate indication of the power value and the time at which it occurred (as identified in Figure 6.30.) The percentage differences indicate that the highest difference exists between the video and waist mounted accelerometer derived TTPPNSW (7.6 ± 1.3%), with the least percentage difference existing between the video and bar mounted accelerometer (3.9 ± 0.8%) and the force platform lying within these ranges (6.5 ± 0.7%).

6.3.4.14 Subject ranking

To investigate further the relative validity of the force platform, bar and waist mounted accelerometers when compared to the video derived results, the mean peak acceleration, force, velocity, peak power with and without system weight, squat depth and time to peak was calculated for each subject. The mean peak values per subject for each variable were ranked. For example, the subject with the highest mean peak acceleration was ranked as (1), the subject with the lowest mean peak acceleration was ranked as (8), this was conducted for the video (Figure 6.33(a)), force platform (Figure 6.33(b)), bar mounted accelerometer (Figure 6.33(c)) and waist mounted accelerometer (Figure 6.33(d)). The difference between the video ranking and the ranking derived from the remaining methods was calculated for each variable previously investigated.

The histograms presented in Figure 6.34 display the difference between the video and the ranking derived from the force platform (a), bar mounted (b) and waist mounted accelerometer (c). The results indicate that the ranking difference for each method is centred about zero, (force platform (0.04 ± 0.12), bar mounted accelerometer (0.01 ± 0.13), waist mounted accelerometer (0 ± 0.11). This suggests that although the force platform and accelerometers may produce significantly different mean peak values for some variables (such as power), the relative ranking of each subject correlates highly with the video. Therefore, a reduction in performance or improvement relative to a previous session and variation between different subjects can still be detected.

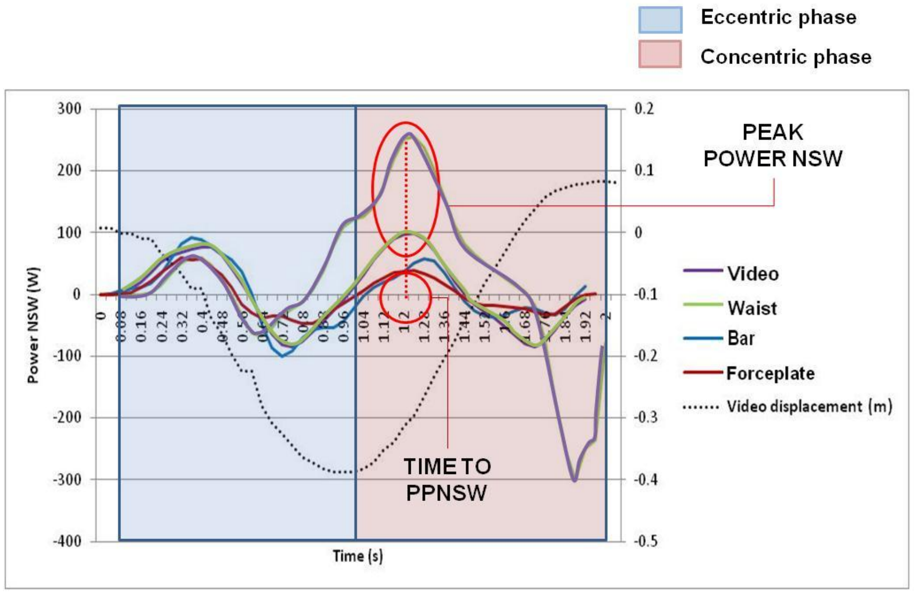


Figure 6.30 Example video, force platform and accelerometer derived TTPPNSW for one squat.

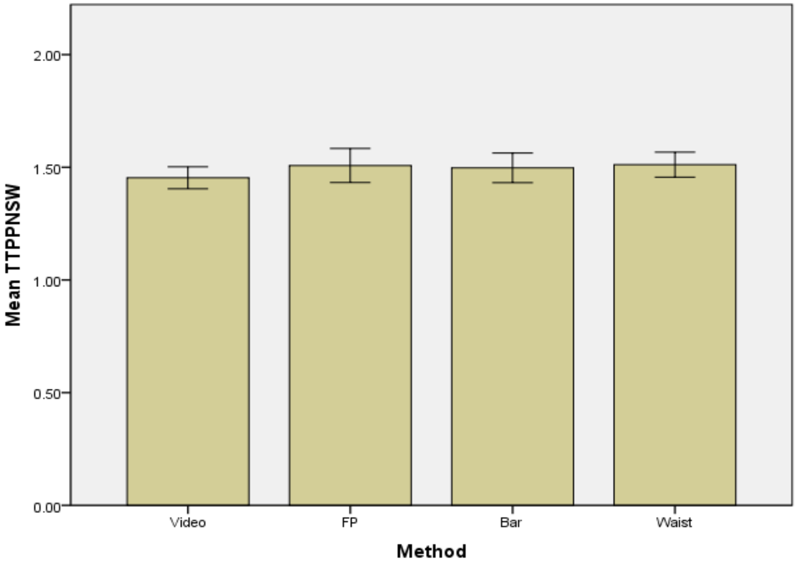


Figure 6.29 Mean peak TTPPNSW and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (s)	1.45 ± 0.02	1.51 ± 0.04	1.50 ± 0.03	1.51 ± 0.03
Std Deviation	0.22	0.34	0.29	0.25
Std Error between means (s)	N/A	0.05 ± 0.05	0.04 ± 0.04	0.06 ± 0.04
Sig. value	N/A	1.19	1.06	1.55
Mean % difference	N/A	3.9± 2.2%	3.0 ± 1.4%	4.2 ± 1.2%

Table 6.10 Statistical analysis of the TTPPNSW results derived from the video, force platform and accelerometers to determine whether significant difference exists.

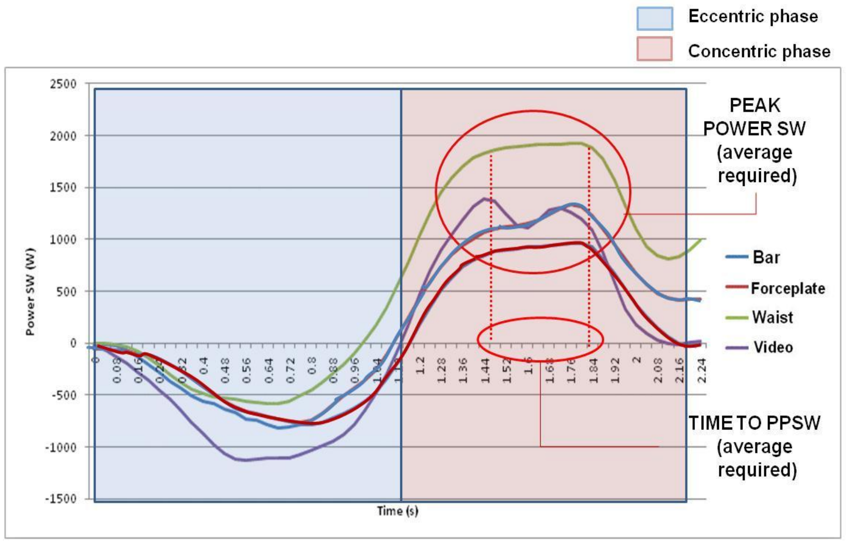


Figure 6.31 Example video, force platform and accelerometer derived TTPPSW for one squat.

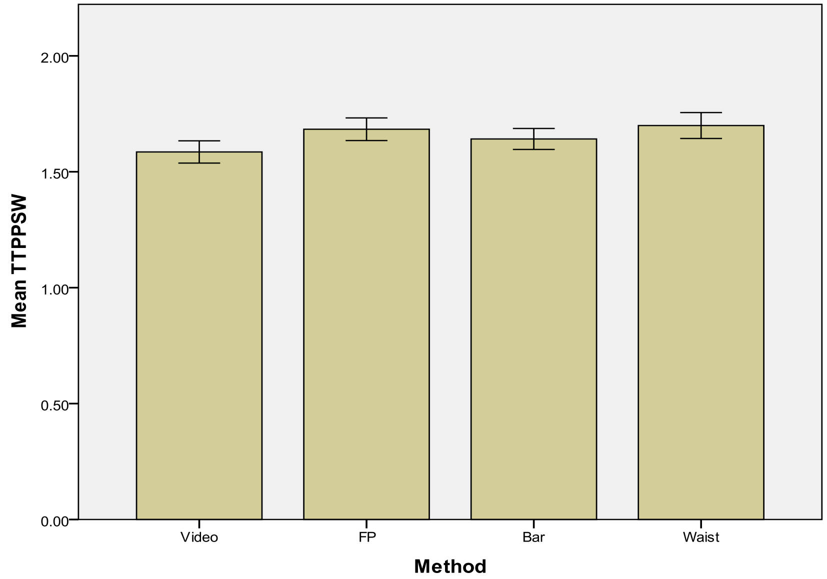


Figure 6.32 Mean peak TTPPSW and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Bar accelerometer	Waist accelerometer
Mean (s)	1.59 ± 0.02	1.68 ± 0.02	1.64 ± 0.02	1.70 ± 0.03
Std Deviation	0.22	0.22	0.20	0.25
Std Error between means (s)	N/A	0.09 ± 0.03	0.06 ± 0.03	0.11 ± 0.04
Sig. value	N/A	2.83	1.68	3.06
Mean % difference	N/A	6.5 ± 0.7%	3.9 ± 0.8%	7.6 ± 1.3%

Table 6.11 Statistical analysis of the TTPPSW results derived from the video, force platform and accelerometers to determine whether significant difference exists.

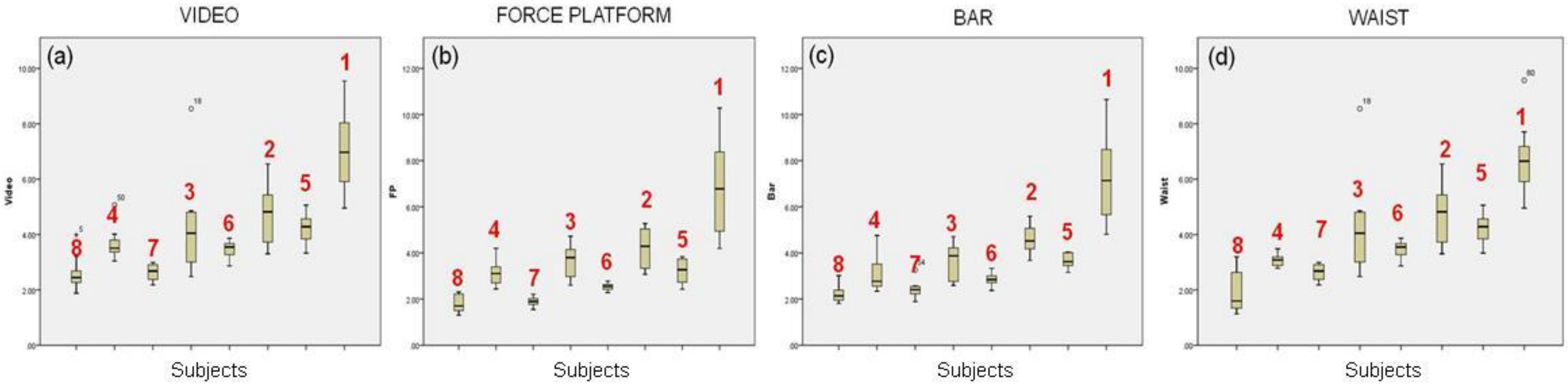


Figure 6.34 Example subject ranking of the mean peak acceleration derived from the video, force platform, bar and waist mounted accelerometers

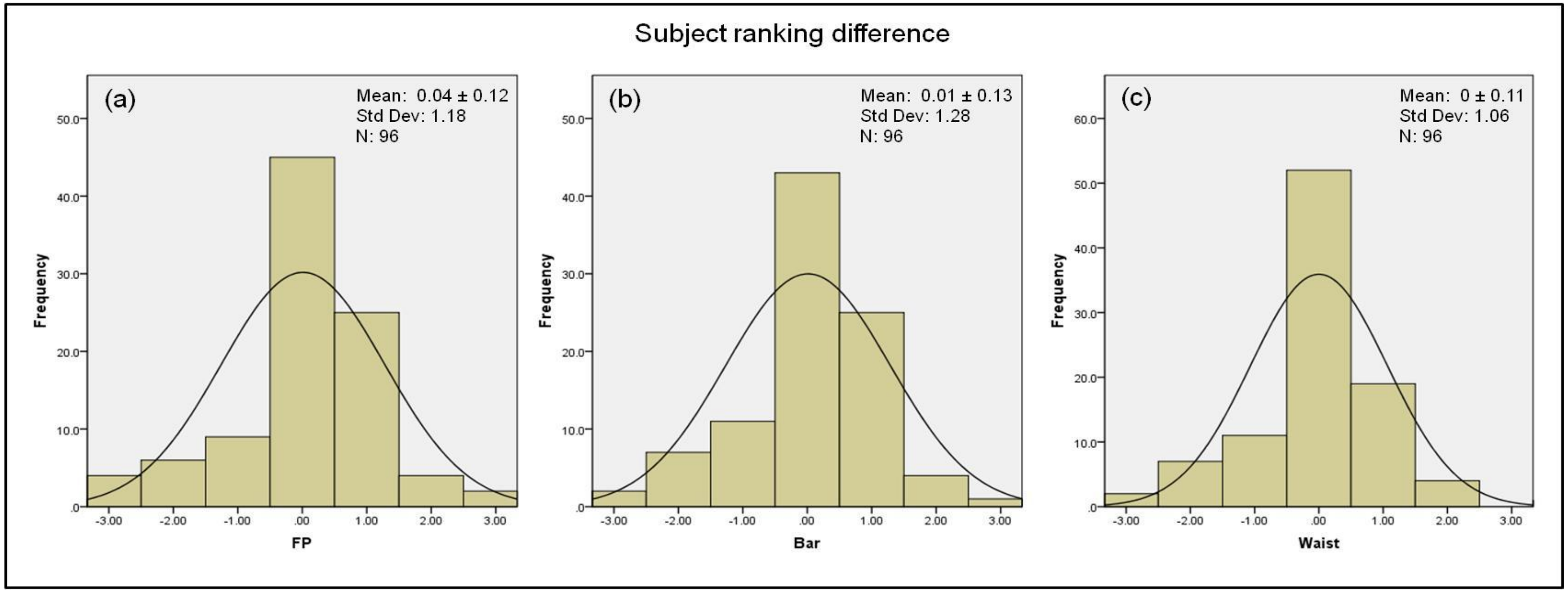


Figure 6.33 The mean difference in subject ranking between video and forceplate, video and bar mounted accelerometer and video and waist mounted accelerometer.

6.4 Case study 1 summary

The levels of significant difference calculated as a result of this Case study are listed in Table 6.13. The results are plotted in Figure 6.35. The chart displays the sig value for each performance variable derived from the force platform, bar and waist mounted accelerometer. The sig value increases as the level of integration to derive the variable increases. For example, the peak squat depth sig value is significantly higher for all three methods following the double integration of acceleration. The peak acceleration and peak force and time to peak acceleration and force sig values are consistent as the force is a product of the acceleration multiplied by the mass (which is constant). The error incurred when acceleration is integrated to calculate velocity is reflected by the increased sig values for each system. This error is propagated when multiplied by the force to derive power (both with and without the system weight). Significant difference increases as velocity becomes a part of the performance variable output. The results suggest that calculating power including the system weight (PPSW) reduces the difference and increases correlation between the video and each method.

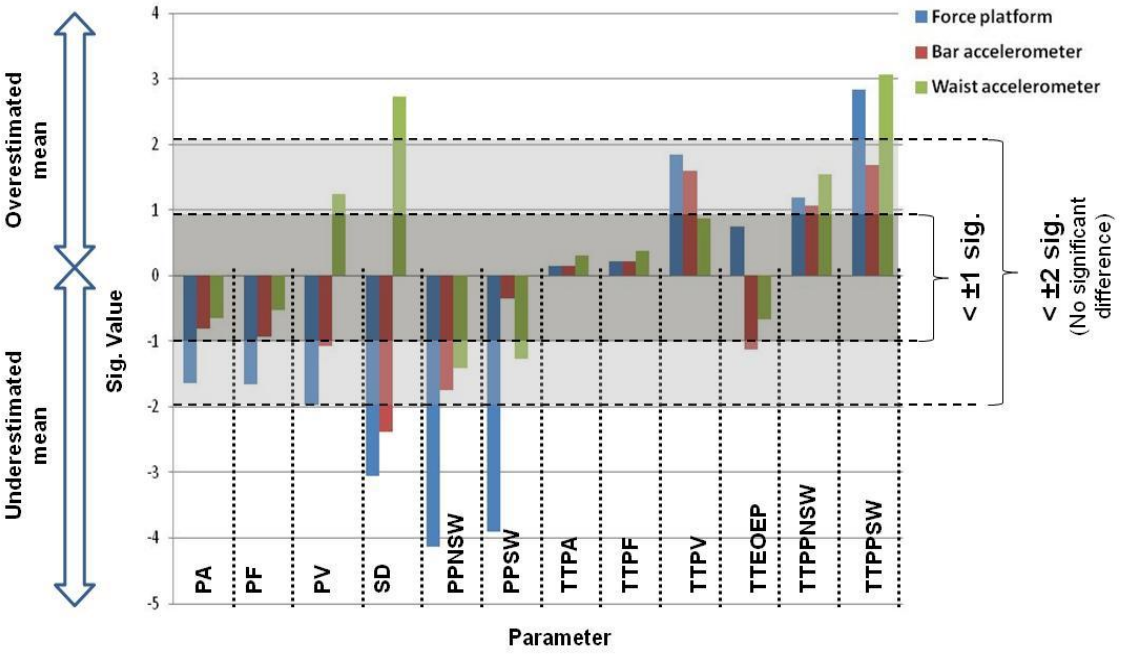


Figure 6.35 Overview of the sig values for each performance variable, generated by the force platform, bar and waist mounted accelerometer when compared to the video results.

Variable	Method	Mean	Std Dev	Std Error between means	Sig. Value	Mean % difference
PA (m/s²)	Video	3.98 ± 0.17	1.52			
	Force platform	3.57 ± 0.19	1.67	-0.42 ± 0.25	**-1.64**	-9.6 ± 1.4
	Bar Acc	3.78 ± 0.19	1.68	-0.21 ± 0.25	**-0.81**	-6.6 ± 1.4
	Waist Acc	3.83 ± 0.18	1.56	-0.16 ± 0.25	**-0.65**	-5.0 ± 1.2
PF (N)	Video	499 ± 31	280			
	Force platform	422 ± 34	301	-76 ± 46	**-1.66**	-11.6 ± 1.8
	Bar Acc	456 ± 34	300	-43 ± 46	**-0.93**	-7.47 ± 1.8
	Waist Acc	476 ± 31	278	-24 ± 44	**-0.53**	-5.4 ± 1.3
PV (m/s)	Video	1.06 ± 0.04	0.33			
	Force platform	0.95 ± 0.04	0.34	-0.11 ± 0.05	**-1.98**	-10.1 ± 1.7
	Bar Acc	1.00 ± 0.04	0.36	-0.06 ± 0.05	**-1.07**	-7.9 ± 2.7
	Waist Acc	1.10 ± 0.04	0.33	0.04 ± 0.05	**0.76**	4.3 ± 1.4
SD (m)	Video	-0.48 ± 0.02	0.18			
	Force platform	-0.40 ± 0.01	0.13	-0.08 ± 0.03	**-3.05**	-17.1 ± 1.3
	Bar Acc	-0.41 ± 0.02	0.21	-0.07 ± 0.03	**-2.38**	-14.0 ± 3.3
	Waist Acc	-0.55 ± 0.02	0.18	0.07 ± 0.03	**2.73**	13.2 ± 3.1
PPNSW (W)	Video	361 ± 31	278			
	Force platform	211 ± 18	162	-149 ± 36	**-4.14**	-29.9 ± 4.7
	Bar Acc	288 ± 27	245	-73 ± 42	**-1.75**	-14.6 ± 4.2
	Waist Acc	302 ± 28	251	-60 ± 42	**-1.41**	-8.6 ± 5.2
PPSW (W)	Video	1386 ± 83	750			
	Force platform	978 ± 61	545	-408 ± 104	**-3.91**	-24.0 ± 3.7
	Bar Acc	1344 ± 86	767	-42 ± 121	**-0.35**	-0.98 ± 5.1
	Waist Acc	1539 ± 86	769	152 ± 123	**1.26**	15.3 ± 4.8
TTPA (s)	Video	1.23 ± 0.03	0.27			
	Force platform	1.23 ± 0.03	0.27	0.006 ± 0.04	**0.14**	1.0 ± 0.9
	Bar Acc	1.23 ± 0.03	0.28	0.006 ± 0.04	**0.14**	0.6 ± 0.7
	Waist Acc	1.24 ± 0.03	0.29	0.014 ± 0.04	**0.30**	1.0 ± 0.9
TTPF (s)	Video	1.23 ± 0.03	0.27			
	Force platform	1.23 ± 0.03	0.27	0.009 ± 0.04	**0.21**	1.3 ± 0.9
	Bar Acc	1.23 ± 0.03	0.28	0.01 ± 0.04	**0.21**	0.9 ± 0.8
	Waist Acc	1.24 ± 0.03	0.29	0.017 ± 0.04	**0.37**	1.3 ± 1.0
TTPV (s)	Video	1.67 ± 0.02	0.22			
	Force platform	1.73 ± 0.02	0.22	0.06 ± 0.03	**1.84**	4.1 ± 0.6
	Bar Acc	1.73 ± 0.03	0.21	0.05 ± 0.03	**1.60**	3.6 ± 0.6
	Waist Acc	1.70 ± 0.03	0.24	0.03 ± 0.04	**0.87**	1.9 ± 0.5
TTEOEP (s)	Video	1.18 ± 0.02	0.22			
	Force platform	1.21 ± 0.03	0.23	0.03 ± 0.04	**0.75**	2.3 ± 0.6
	Bar Acc	1.14 ± 0.03	0.23	-0.04 ± 0.04	**-1.13**	-13.2 ± 1.1
	Waist Acc	1.16 ± 0.03	0.25	-0.02 ± 0.04	**-0.66**	-2.5 ± 0.8
TTPPNSW (s)	Video	1.45 ± 0.02	0.22			
	Force platform	1.51 ± 0.04	0.34	0.05 ± 0.05	**1.19**	3.9 ± 2.2
	Bar Acc	1.50 ± 0.03	0.29	0.04 ± 0.04	**1.06**	3.0 ± 1.4
	Waist Acc	1.51 ± 0.03	0.25	0.06 ± 0.04	**1.55**	4.2 ± 1.2
TTPPSW (s)	Video	1.59 ± 0.02	0.22			
	Force platform	1.68 ± 0.02	0.22	0.09 ± 0.03	**2.83**	6.5 ± 0.7
	Bar Acc	1.64 ± 0.02	0.20	0.06 ± 0.03	**1.68**	3.9 ± 0.8
	Waist Acc	1.70 ± 0.03	0.25	0.11 ± 0.04	**3.06**	7.6 ± 1.3

Table 6.12 Overview of the squat statistical analysis for each performance variable derived from the video, force platform and accelerometers and resultant difference significance.

A distinctive peak is not present in the PPSW profile, the gradual curve reduces the ability to identify the time to peak power. Identifying the time to peak power is easier using the PPNSW method given the distinctive peak, therefore the sig values are much lower and the difference is less significant. Although calculating the peak power is prone to error due to the combined effect of the force and velocity inaccuracies, the ranking of performance can still be achieved (reflected by the low ranking mean difference present using each system when compared to video analysis (force platform (0.04 ± 0.12), bar mounted accelerometer (0.01 ± 0.13) and waist mounted accelerometer (0.00 ± 0.11)). The subject who produced the most power according to video analysis, will also have produced the most power according to the force platform and accelerometer analysis. The variables increase or decrease relative to one another in the same manner as the video derived results, indicating that a waist or bar mounted accelerometer can be used to monitor integration dependent variables (such as power) relatively.

Overall, the waist mounted and bar mounted accelerometer have similar levels of correlation with the video, each exhibiting an increase in sig value as the level of integration increases. The waist mounted accelerometer on average produced lower mean differences and sig values than the bar mounted accelerometer, however, the difference between the accelerometers was not significant (mean sig value 0.76). Therefore, the location of the accelerometer does not significantly affect the results when monitoring a simple linear exercise. The low sig values derived from the bar and waist mounted accelerometers for the peak acceleration (-0.81 and -0.65), force (-0.93 and -0.53) and velocity (-1.07 and 0.76) indicate that significant difference does not exist when compared to video derived results and can therefore both be used to monitor simple linear exercises. As the demand for additional performance data and the exercise complexity increases, higher accuracy is required (for which gyroscope technology is required). Whether a linear exercise of increased complexity can be monitored using a waist mounted accelerometer to derive take off velocity and jump height is discussed in the following section.

6.5 Case study 2

To progress from the analysis of the squat (a linear, whole body movement), analysis of an unloaded squat jump was conducted (a linear, whole body movement requiring time in flight). The method outlined in Section 6.2 was followed with the same eight healthy subjects (five male and three female) with a mean age of 23.9 ± 2.3 years and body mass of 78.8 ± 25.4kg. Only the waist mounted accelerometer was used as a bar was not required and each subject performed two squat jumps. The validity of one triaxial accelerometer located on the waist and one force platform in relation to video analysis was investigated to determine whether the increased explosive nature of a squat jump reduced validity between each method. Analysis of the squat jump differed as rep separation was not required. Each squat jump was completed individually (not as a set), this allowed the subject to produce as much power as possible. The variables listed below were derived from the video, forceplate and waist mounted accelerometer for each squat jump, however, the take off velocity and jump height remain as the focus of the study.

- Peak acceleration (PA)
- Peak force (PF)
- Peak velocity (TOV)
- Jump height (JH)
- Peak power no system weight (PPNSW)
- Peak power system weight (PPSW)
- Time to PA(TTPA)
- Time to PF (TTPF)
- Time to TOV (TTTOV)
- Time to PPNSW (TTPPNSW)
- Time to PPSW (TTPPSW)

6.5.1 Calculating jump height

As discussed in Chapter 3, there are numerous calculations used to estimate jump height, depending on the equipment available (Beynonn and Johnson 1996). Time in the air (TIA) is a commonly used method, the vertical displacement of the centre of mass (COM) is calculated using an equation of uniform acceleration (Beynonn and Johnson

1996). A jump is defined as “a vertical displacement achieved by a COM from take off to the vertex of the flight trajectory” (Moir 2008). This requires consideration of the time of flight only, however, using the method, it is assumed that the position of the COM is the same at the beginning before take-off and upon landing, subsequent questioning of TIA calculation validity has arisen since the COM might deviate from the initial position (Bosco 1983).

Another method involves calculating the vertical velocity of the COM at take off by integrating the force trace and using an equation of uniform acceleration to determine the jump height. This avoids the assumption that the COM is the same at takeoff and landing but does not account for the change in vertical displacement that will occur due to joint extension. It is suggested that the vertical displacement can be calculated from using motion based systems (Hatze 1998). The two calculations are outlined below.

1. TIA = ½ g(t/2)2

2. TOV = TOV^2/2g

Before conducting the main study using a waist mounted accelerometer, preliminary testing was conducted to investigate the effect of the different jump height calculation methods and to determine which method would most suitable for the main study.

6.5.1.1 Jump height preliminary testing

A force platform operating at 1000Hz was used to collect GRF data for three unloaded squat jumps performed by one subject. The subject was instructed to remain stationary for the first few seconds of data collection to ensure that the initial velocity was set to zero. The subject was also instructed not to use arm propulsion during the jump. The net force calculated from the force platform GRF is presented in Figure 6.36(a). The eccentric and concentric phases were identified using video analysis, whilst the flight time corresponds to the period of zero net force that occurs after the concentric phase. Method 1 relies upon the identification of flight time to calculate jump height.

Only GRF data preceding the jump was required to derive the take off velocity. Therefore, only the concentric and eccentric phases identified in Figure 6.36(b) were used to derive the required kinematic data. In order to calculate velocity, the acceleration was first calculated using Newton's Second Law (Force = Mass x acceleration). The acceleration data were then integrated to calculate the velocity profile. The resultant velocity profile is presented in Figure 6.36 (b). Method 2 relies upon the derivation of take off velocity to calculate jump height. The jump height for each squat jump was calculated using the three methods and compared to the jump height derived from video analysis.

6.5.1.2 Jump height preliminary results

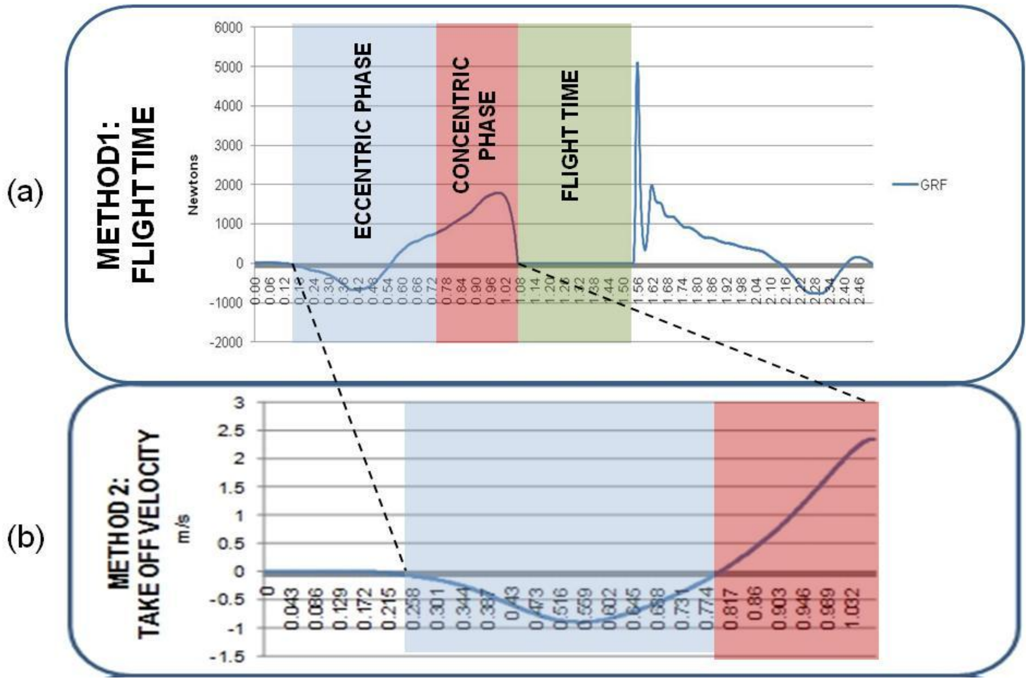


Figure 6.36 The data required to calculate jump height using two different methods

The results from the preliminary test are presented in Table 6.14. The results for each method were plotted in Figure 6.37 against the jump height derived from the video displacement data. The difference between the jump heights calculated using methods 1 and 2 range from 0.001 to 0.01 m. The difference between methods 1 and 2 and the video displacement ranged from 0.01 to 0.02 m. These results suggest that using method 1 or 2 does not significantly affect the resultant jump height calculation.

CALCULATING JUMP HEIGHT FOR A SQUAT JUMP			
Method		**1**	**2**
Equation		1/2 *g*(*t* / 2)2	TOV2 / 2*g*
Data needed		Flight time	Take off Velocity
Results(m)	**Jump 1**	**0.27 m**	**0.27 m**
	Jump 2	**0.23 m**	**0.23 m**
	Jump 3	**0.26 m**	**0.27 m**

Table 6.13 Jump height results using each method of calculation

6.5.1.3 Jump height preliminary study summary

The choice of method is dependent upon the practitioner's view of "what constitutes a jump." The additional calculations required to obtain the jump height in relation to COM movement does not provide additional performance knowledge than methods 1 or 2. Method 1 is reliant on the ability to determine when the subject leaves the ground and lands, this is feasible using video and force platform technology. Whether identification of each jump phase is feasible using accelerometer technology alone requires further investigation and is discussed in Section 6.5.2. As the results using method 2 were highly correlated with method 1 and video displacement, it is suggested that it is the most feasible method for determining jump height using accelerometer technology due to the simplicity and reduced error accumulation. Whether the acceleration data collected using a waist mounted accelerometer could be used to determine jump height using the take off velocity, was investigated in the main study.

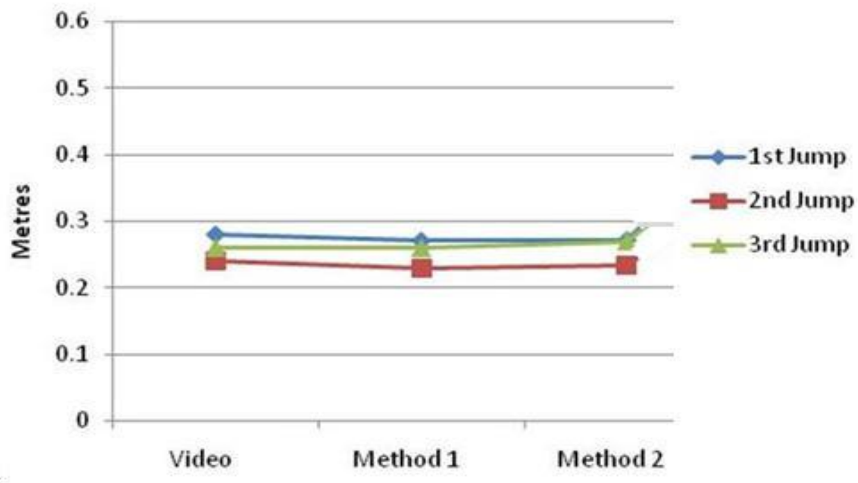


Figure 6.37 Jump height results using each method of calculation against the video displacement data

6.5.2 Monitoring jump height using a waist mounted accelerometer

The primary objective of the study was to compare the jump height results calculated using the take off velocity derived from the video, force platform and waist mounted accelerometer. Statistical analysis was conducted to investigate whether significant difference existed between each method using the same staistical methods used in Case Study 1. The take off velocity (TOV), time to take off velocity (TTTOV) and jump height (JH) were all compared.

The acceleration profiles derived from the video, force platform and accelerometer and identified phases of movement are presented in Figure 6.38. Digitisation of both the waist and bar mounted accelerometer was required to compare the video and accelerometer derived data. The eccentric and concentric phases have been identified using the video displacement data, the flight phase has been identified using the force platform. The period of zero GRF following the concentric phase corresponds to the time in flight (TIA). A summary of the four phases is given below:

1. **First negative peak:** The squat jump acceleration profile initially has a negative phase as the subject contracts eccentrically and the knees flex prior to the positive (concentric) phase of the movement.
2. **First positive peak:** The positive phase results in a change in acceleration and force direction until a positive peak is reached. This is the driving phase of the movement; the continued acceleration of the subject during flight phase is included in the video and accelerometer trace.
3. **Second negative peak:** Maximum jump height is reached and the subject experiences negative acceleration during the return to the ground. Negative acceleration may continue as the subject absorbs the landing and flexes the knees.
4. **Second positive peak:** The subject contracts concentrically to return to the initial standing position. The legs are used to drive against gravity; therefore a positive acceleration is experienced.

Although statistical analysis is required to quantify the relative and absolute validity between video-force platform and video- accelerometer technology, the results indicate that the three phases typical of squat profile (as identified in Chapter 5) are present in the initial phases of the squat jump. This is inevitable as the squat jump involves the same gross movement as the squat to initate the jump. Due to the nature of the squat jump, a landing phase must occur, therefore, a fourth phase was also identified as the subject returns to the initial standing position. The fourth phase is highly influenced by the third phase since the amount of flexion generated by the subject on, landing determines how much extension and resultant positive acceleration is required to return to the original standing position. The large negative peak present in the squat jump profile is due to the negative acceleration as the subject returns to the ground following the jump phase (free fall). The subject continues to decelerate as the knees bend to absorb the shock of the landing.

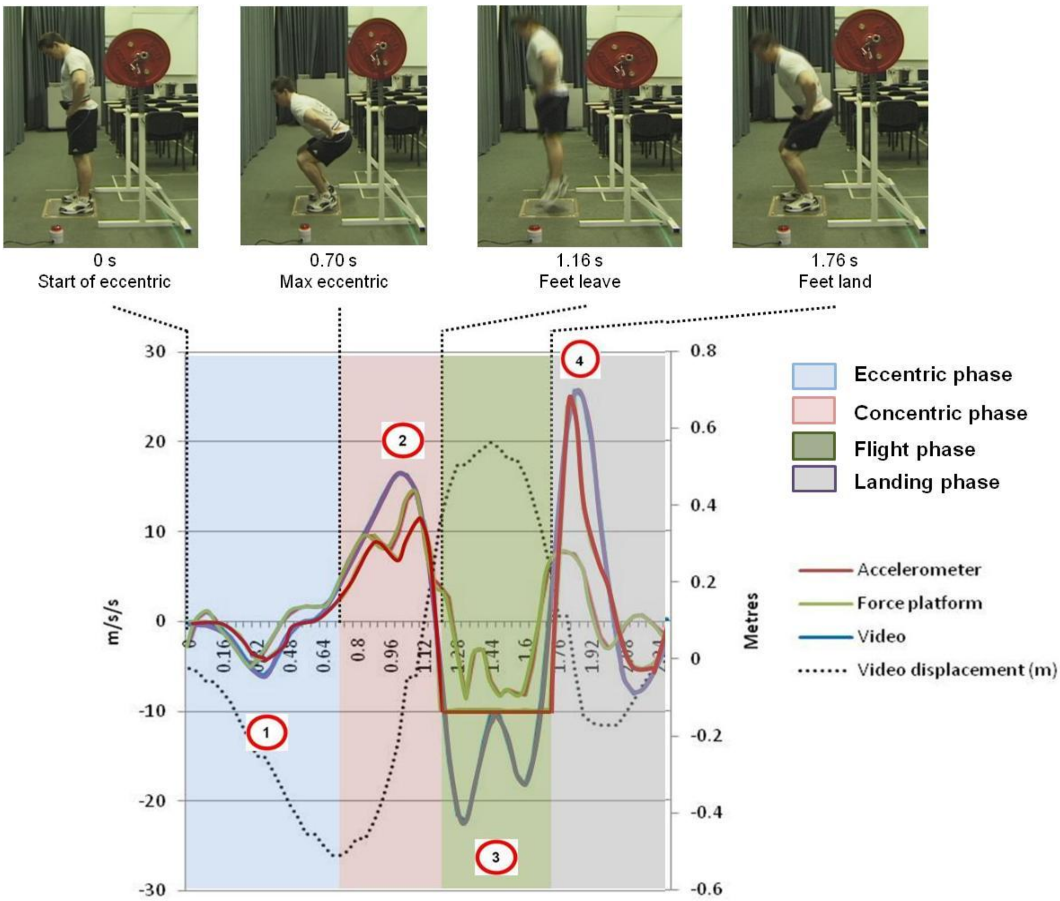


Figure 6.38 Comparison of force platform, video and accelerometer derived acceleration profiles for a squat jump and identification of the key components

The preliminary testing indicated that the most suitable method to estimate jump height involved calculation of the take off velocity (TOV). This method reduces the integration error and eliminates the need to analyse the latter phases of the jump where the noise and error seem to increase in the accelerometer trace. Integration of the acceleration data was conducted to obtain video, force platform and accelerometer velocity and power profiles and resultant jump height estimations. The results are discussed in the following section.

6.5.3 Squat jump results

An example of the velocity profiles derived from the video, force platform, waist mounted accelerometer for one squat is presented in Figure 6.39. The mean take off velocity and error bars (at a 95% confidence interval) for each system are presented in Figure 6.40, whilst the mean, standard deviation, standard error between means and level of significance are listed in Table 6.15. The results indicate that greatest difference exists between the video and waist accelerometer (SEM (0.23 ± 0.19 m/s) and sig value (1.23)). However, the sig value suggests that this difference is not significant (it is within ± 2). The force platform results indicate higher correlation with the mean peak velocity derived from the video (SEM (0.06 ± 0.20 m/s), sig value (0.29). In contrast to the squat case study results, the force platform shows higher correlation with the video data. This is attributed to the high explosive nature of the exercise which improves the ability to generate accurate GRF data. Both the force platform and waist mounted accelerometer exhibit low mean percentage differences (force platform (2.83 ± 2.37%) and accelerometer (-6.24 ± 5.15%)).

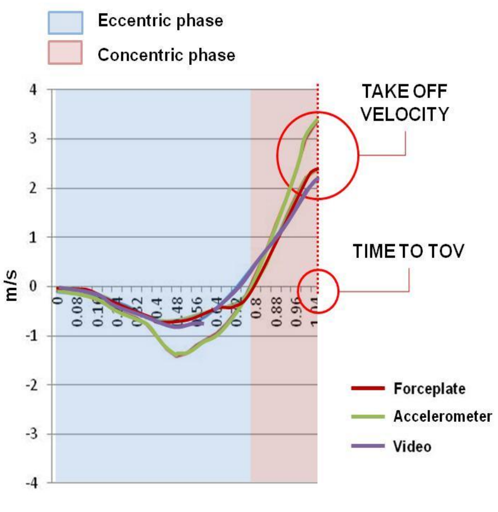


Figure 6.39 Example video, force platform and accelerometer derived take off velocity for one squat jump.

The take off velocity was used to calculate the jump height. The mean peak jump height and error bars (at a 95% confidence interval) for each system are presented in Figure 6.41, whilst the mean, standard deviation, standard error between means and level of significance are listed in Table 6.16. The results are consistent with the take off velocity but the error is slightly increased (force platform SEM (0.03 ± 0.06), sig value

(0.53) and accelerometer SEM (0.07 ± 0.05), sig value (1.29)). Although the waist mounted accelerometer results are not significantly different, the results suggest that the overestimation of the take off velocity present in the accelerometer data is amplified when calculating the jump height. The difference between the take off velocity derived from the video and force platform is plotted in Figure 6.42 (a). The difference between the take off velocity derived from the video and force platform is centred about zero (Figure 6.42 (a)). The accelerometer histogram Figure 6.42 (b) displays a wide range of error (supported by the standard deviation (0.52)). This relationship is mirrored in the jump height results, the accelerometer has a wide variation of error (standard deviation 0.17 (Figure 6.42 (d))) compared to the force platform which is again centred about zero and has a smaller range of error (standard deviation 0.06 (Figure 6.42 (c))).

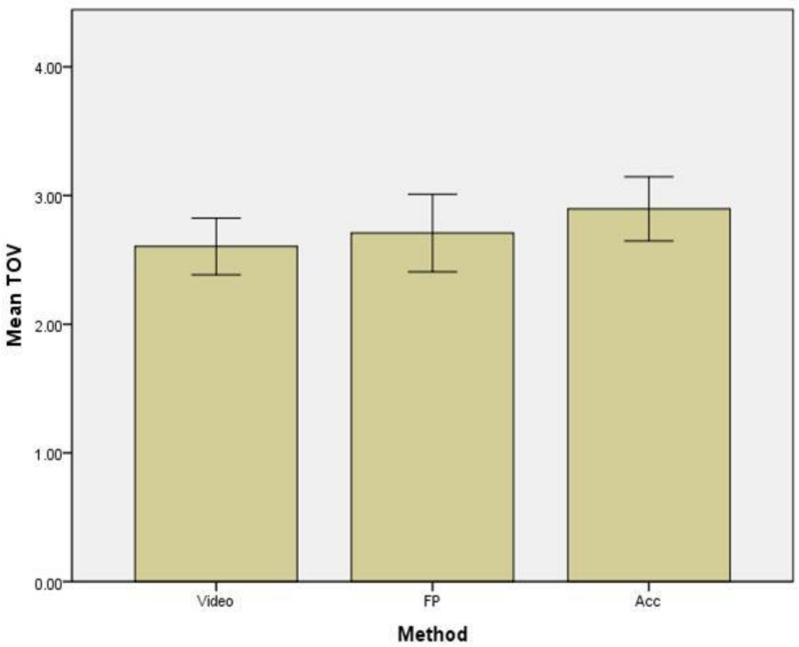


Figure 6.40 Mean peak TOV and error bars (95% CI interval) derived using each method.

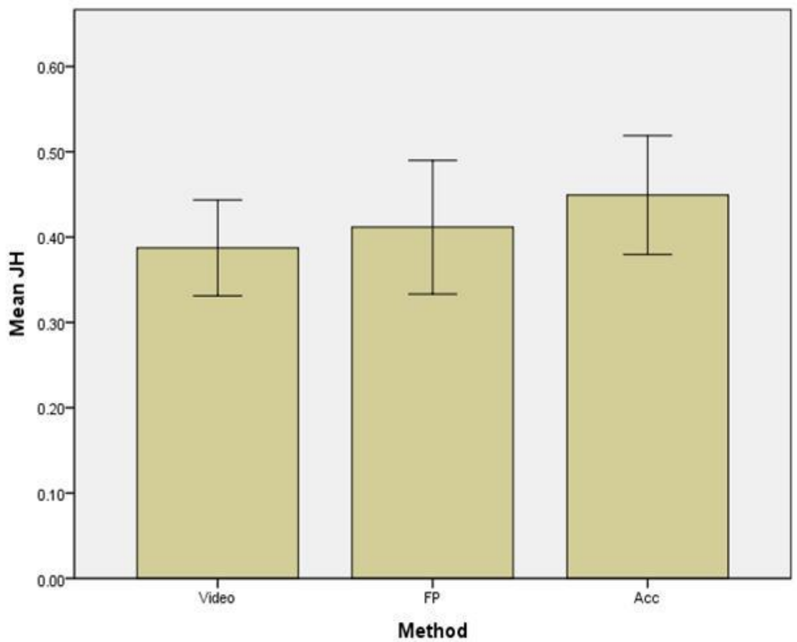


Figure 6.41 Mean peak jump height and error bars (95% CI interval) derived using each method.

Statistic	Video	Force platform	Accelerometer
Mean (m/s)	2.71 ± 0.15	2.76 ± 0.13	2.94 ± 0.10
Std Deviation	0.56	0.52	0.47
Std Error between means (m/s)	N/A	0.06 ± 0.20	0.23 ± 0.19
Sig. value	N/A	**0.29**	**1.23**
Mean % difference	N/A	2.83 ± 2.37	6.24 ± 5.15

Table 6.16 Statistical analysis of the TOV results derived from the video, force platform and accelerometers to determine whether significant difference exists.

Statistic	Video	Force platform	Accelerometer
Mean (m)	0.39 ± 0.04	0.41 ± 0.04	0.46 ± 0.03
Std Deviation	0.16	0.14	0.13
Std Error between means (m)	N/A	0.03 ± 0.20	0.07 ± 0.19
Sig. Value	N/A	**0.53**	**1.29**
Mean % difference	N/A	6.98 ± 4.17	8.96 ± 10.19

Table 6.17 Statistical analysis of the jump height results derived from the video, force platform and accelerometers to determine whether significant difference exists.

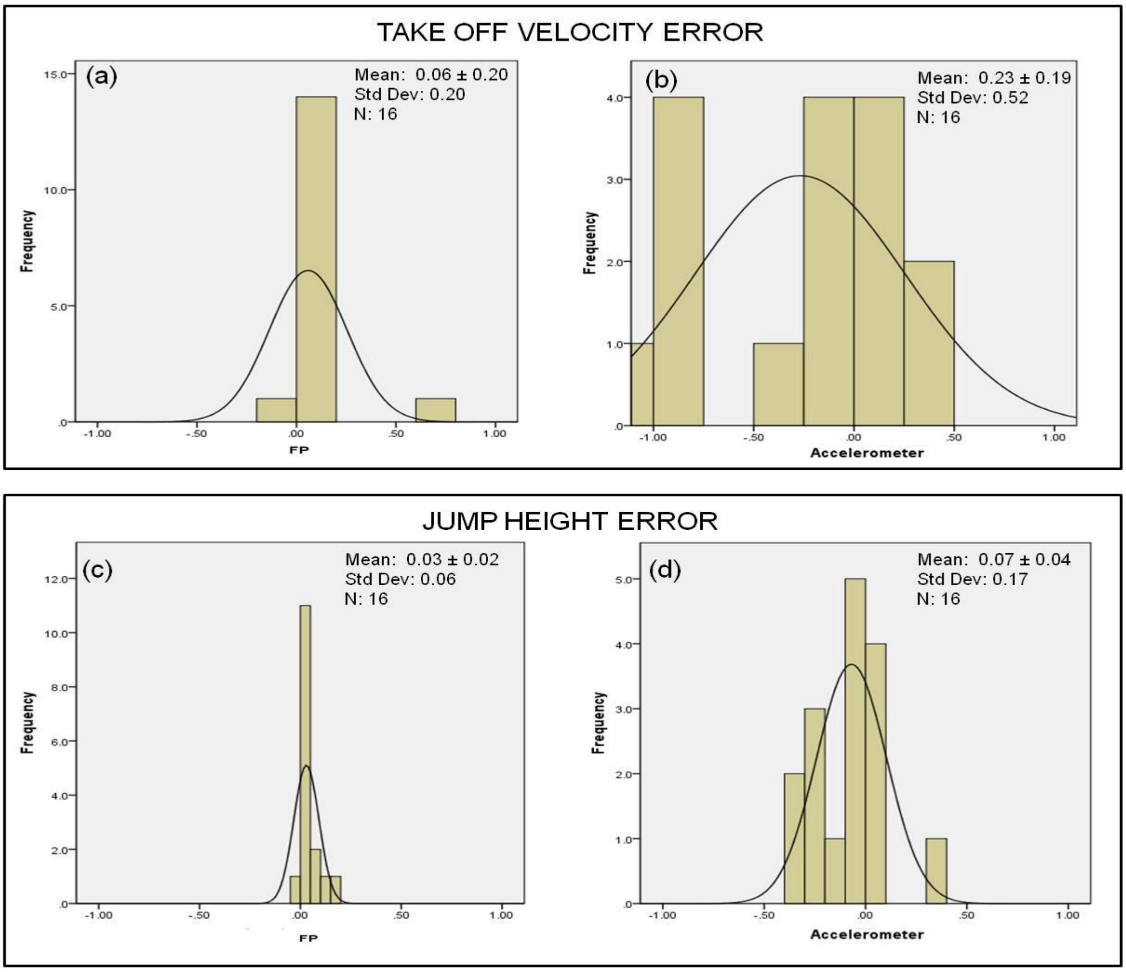


Figure 6.42 The difference between the velocity (m/s) and jump height (m) derived from the video, force platform and accelerometers.

Although the focus of this study was to investigate the ability to derive the take off velocity and resultant jump height using a waist mounted accelerometer, the performance variables collected for the squat were also derived for each squat jump. The levels of significant difference calculated as a result of this case study are listed in Table 6.17. The results are plotted in Figure 6.43. The mean, standard deviation, standard error between means, level of significance and mean percentage difference are listed in Table 6.3 for each performance variable. The results indicate that the force platform exhibits much higher correlation with the video for the squat jump analysis (ranging from 0.14 to -1.30) in comparison to the squat analysis (ranging from 0.14 to -4.14). The squat jump requires more power to be exerted than during a squat, the explosive nature of the exercise produces higher rates of acceleration (video 12.02 ± 0.70, force platform 11.87 ± 0.67 and accelerometer 11.12 ± 0.65). As force is a product of mass and acceleration, the ability to detect acceleration using a force platform is increased, therefore the overall correlation between the video and force platform for each performance variable is improved.

Variable	Method	Mean	Std Dev	Std Error between means	Sig. Value	Mean % difference
PA (m/s^2)	Video	12.02 ± 0.70	2.71			
	Force platform	11.87 ± 0.67	2.61	-0.16 ± 0.97	**-0.16**	-0.30 ± 3.66
	Accelerometer	11.12 ± 0.65	2.52	-0.90 ± 0.96	**-0.94**	-6.76 ± 3.07
PF (N)	Video	930 ± 61	235			
	Force platform	918 ± 60	231	-12 ± 85	**-0.14**	-0.30 ± 3.66
	Accelerometer	855 ± 56	216	-76 ± 82	**-0.92**	-6.74 ± 3.07
TOV (m/s)	Video	2.71 ± 0.15	0.56			
	Force platform	2.76 ± 0.13	0.52	0.06 ± 0.20	**0.29**	2.83 ± 2.37
	Accelerometer	2.94 ± 0.10	0.47	0.23 ± 0.19	**1.23**	6.24 ± 5.15
JH (m)	Video	0.39 ± 0.04	0.16			
	Force platform	0.41 ± 0.04	0.14	0.03 ± 0.06	**0.54**	6.98 ± 4.17
	Accelerometer	0.46 ± 0.03	0.13	0.07 ± 0.05	**1.28**	8.96 ± 10.19
PPNSW (W)	Video	1891 ± 188	729			
	Force platform	1587 ± 170	660	304 ± 254	**1.20**	12.7 ± 11.0
	Accelerometer	2124 ± 178	689	234 ± 259	**0.90**	16.73 ± 4.79
PPSW (W)	Video	3587 ± 327	1267			
	Force platform	3459 ± 290	1124	-128 ± 437	**-1.30**	2.74 ± 8.57
	Accelerometer	3856 ± 306	1186	269 ± 448	**1.60**	10.92 ± 5.06
TTPA (s)	Video	1.04 ± 0.07	0.25			
	Force platform	1.05 ± 0.07	0.28	0.02 ± 0.10	**0.15**	1.34 ± 2.51
	Accelerometer	1.06 ± 0.07	0.27	0.03 ± 0.10	**0.26**	2.39 ± 1.39
TTPF (s)	Video	1.04 ± 0.07	0.25			
	Force platform	1.05 ± 0.07	0.28	0.02 ± 0.10	**0.15**	1.34 ± 2.51
	Accelerometer	1.06 ± 0.07	0.27	0.03 ± 0.10	**0.26**	2.39 ± 1.39
TTTOV (s)	Video	1.19 ± 0.06	0.25			
	Force platform	1.18 ± 0.07	0.27	-0.01 ± 0.09	**-0.03**	-0.54 ± 1.01
	Accelerometer	1.20 ± 0.07	0.27	0.02 ± 0.09	**0.18**	1.36 ± 0.65
TTPPNSW (s)	Video	1.12 ± 0.06	0.25			
	Force platform	1.14 ± 0.07	0.27	0.03 ± 0.09	**0.26**	2.03 ± 0.97
	Accelerometer	1.17 ± 0.06	0.27	0.05 ± 0.09	**0.59**	5.18 ± 2.65
TTPPSW (s)	Video	1.22 ± 0.07	0.28			
	Force platform	1.39 ± 0.11	0.44	0.16 ± 0.13	**1.21**	13.53 ± 6.96
	Accelerometer	1.14 ± 0.07	0.27	-0.08 ± 0.79	**-0.79**	-4.90 ± 4.66

Table 6.14 Overview of the squat jump statistical analysis for each performance variable derived from the video, force platform and accelerometers and resultant difference significance.

The chart displays the sig value for each performance variable derived from the force platform and waist mounted accelerometer. Once again, the sig value increases as the level of integration increases to derive the variable. The error does not cause the results to be significantly different from the video. Similar to the results produced by the squat analysis, determining the time to peak power without the system weight is more accurate than when the system weight is included. Overall, the results indicate that a waist mounted accelerometer can provide an estimation of take off velocity and resultant jump height but force platform technology is required to increase accuracy for explosive, complex exercises performed at an elite level (force platform sig value is lower (0.29) compared to the accelerometer sig value (1.23)).

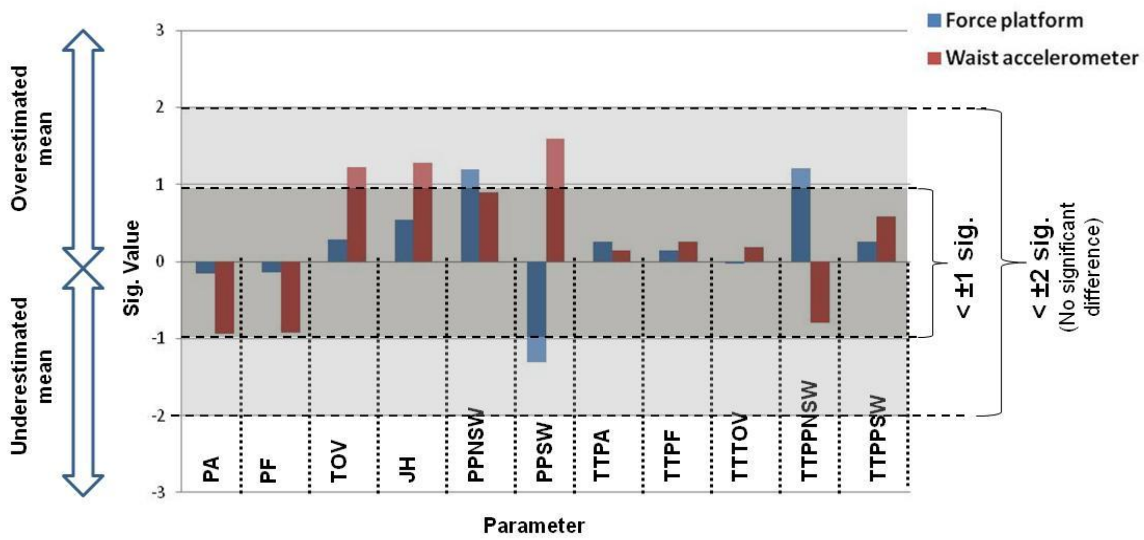


Figure 6.43 Overview of the sig values for each performance variable generated by the force platform, bar and waist mounted accelerometer when compared to the video results.

To determine whether the correlation between the video and waist mounted accelerometer derived results decreased as the exercise complexity increased (from the squat to the squat jump) the sig values for the peak acceleration, force, velocity and take off velocity, squat depth and jump height and peak power with and without system weight were compared. The results are presented in Figure 6.44. The waist mounted accelerometer correlation with the video for the derived peak acceleration, force, velocity and peak power with system weight is higher for the squat analysis than the squat jump analysis. The squat depth results are significantly different from the video, this is expected due to the double integration of the acceleration data. The peak power without system weight (PPNSW) correlates more with the video for the squat jump analysis rather than squat analysis. Nonetheless the waist mounted accelerometer exhibits a higher level of correlation with the video derived results when monitoring the squat rather than squat jump (a higher level of exercise complexity).

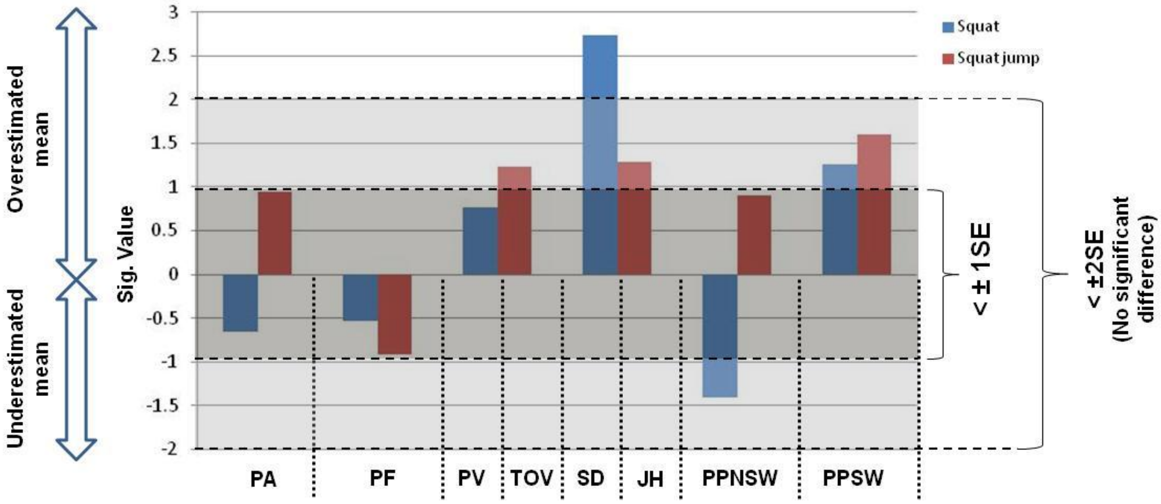


Figure 6.44 Overview of the sig values derived from the waist mounted accelerometer for the squat and squat jump.

The decreased correlation between the video and waist mounted accelerometer for monitoring the squat jump could be attributed to two causes. The first cause is the increase in momentum experienced during the squat jump due to the explosive nature (See Figure 6.45 (a), (b) and (c)). This momentum might cause the waist mounted accelerometer to rotate more than it would during a squat despite the fact that it is a predominantly linear movement. The placement of the accelerometer around the waist means that it would rotate as the spine flexes (b). As the power is exerted and the subject enters the flight phase, momentum increases the rotation experienced by the accelerometer (c). The second cause of decreased correlation between the video and waist mounted accelerometer during the squat jump might be attributed to the increased difficulty in accurately monitoring the location of the accelerometer in the video images during the jump phase. As the subject movement becomes more explosive the location of the accelerometer is harder to identify (see Figure 6.45 (c)).

Both sources of error would combine to increase the difference between the video and accelerometer, however, the difference for each variable is not significant (see Table 6.17). Although the difference between the video and accelerometer increases when a dynamic jump is included in a predominantly linear exercise (squat jump), the results indicate that a waist mounted accelerometer can be used to monitor performance of simple, linear exercises such as the squat or squat jump. As the demand for additional performance data and the exercise complexity increases, higher accuracy is required (for which gyroscope technology is required).

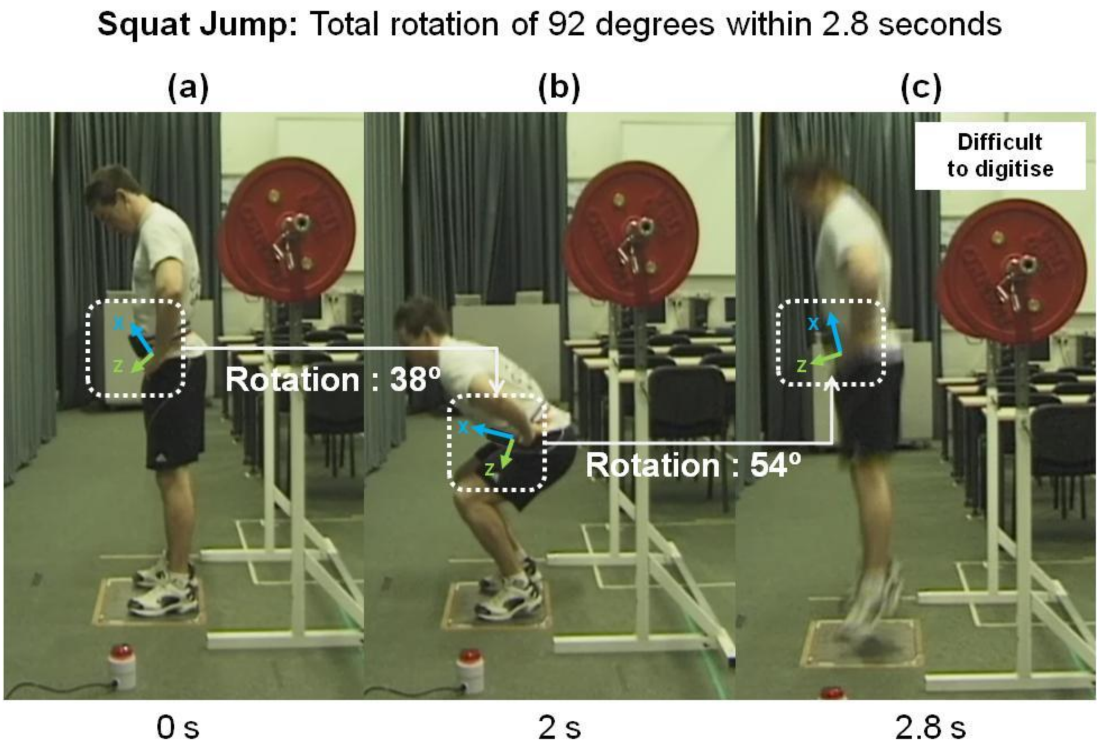


Figure 6.45 Increased rotation of the accelerometer and digitisation error during a squat jump.

6.6 Brief Chapter summary

TARGET OBJECTIVE:

Analyse the execution of simple linear exercises to determine the ability of a simple tri-axis accelerometer (without gyroscopes) to monitor simple linear exercise.

TARGET RESEARCH QUESTION:

Does an accelerometer exhibit high correlation with video analysis when monitoring simple exercises?

The squat results indicate that the bar and waist mounted accelerometer consistently exhibit differences that are not significant (sig values less than 2) when compared to the video derived results. The force platform correlated the least with the video derived results for the squat. This is attributed to the nature of the movement which was not as explosive as the squat jump and does not produce high rates of acceleration to be detected by the force platform. Although the squat movement is linear, flexion of the spine and resultant deviation of the waist and bar mounted accelerometer from a linear path is detected using video analysis but not detected by the force platform. The force generated by the lower body is not necessarily the same amount of force exerted by the upper body following extension of the spine.

A waist mounted accelerometer is more subject to erroneous acceleration during a squat jump due to the effect of the momentum and does not exhibit the same levels of absolute validity derived from the force platform. The higher rates of acceleration required to execute a squat jump increases the force platform absolute validity when compared to video analysis. The bar and waist mounted accelerometers show higher absolute validity when the level of integration and combination of variables required is lower (for example, the peak acceleration and peak force require little data manipulation, whilst, the squat depth and peak power require integration and a combination of variables). The correlation between the video and waist mounted accelerometer is lower for the squat jump than the squat due to the explosive nature of the exercise which inflicts rotation on the device and increases the error of the video digitisation process. However, this difference is not significant, indicating that the waist mounted accelerometer can monitor both squat and squat jump performance at a recreational level. All three systems exhibited high relative validity (identification of the time at which each peak variable occurred) when compared to the video results. The subject ranking results across all performance variables indicate that accelerometers can be used to monitor performance across sessions and between subjects. An increase or decrease in performance can be detected which correlates *relatively* to the video derived results.

Does accelerometer location affect correlation with video analysis?

The waist mounted accelerometer on average produced lower mean differences and sig values than the bar mounted accelerometer for the squat analysis. However, the difference between the accelerometers was not significant (mean sig value 0.76). Both devices exhibited high relative validity (subject ranking and time to peak differences were consistently low). Therefore, the location of the accelerometer does not significantly affect the results when monitoring a simple linear exercise. Although the bar mounted accelerometer results were not significantly different, it is suggested that rotation of the device may have occurred as the bar attachment prototype did not fully prevent rotation of the device during a linear movement. Redesigning an attachment that prevents rotation of the bar mounted accelerometer would increase the range of exercises able to be monitored and provide addtional data regarding bar trajectory that a waist mounted accelerometer would not provide.

How is power output affected when system weight is not included in the force calculation?

Calculating peak power without system weight (PPNSW) and with system weight (PPSW) produced significantly different power profiles. Using the net force rather than the total force resulted in negative values that were multiplied by negative velocity values producing a positive power result. This could cause inaccurate identification of the peak power value and the time at which it occurred. True power lies in the concentric phase where work is being done against gravity, therefore, the application of this method to a real time monitoring system is reliant upon being able to distinguish between the eccentric and concentric peak. In contrast, including the system weight in the power calculation (PPSW) causes the same reduction in force but the values are not centred about zero. Therefore, negative force values do not occur. This has a significant impact on the power profile as the negative and positive phases present in the velocity profile influence the force profile. Both power calculation methods exhibit high sig values and reduced correlation with the video due to the effect of integration and combining variables. However, the subject ranking results indicate that the difference is consistent allowing each subject to be ranked in the same order as that derived from the video. Therefore, using either method produces results that are *relatively* correlated with the video, whilst, determining the time to peak power is easier to achieve when the system weight is not included due to the distinguished peak.

What are the advantages and disadvantages of using force platform, waist mounted and bar mounted accelerometers to monitor simple exercises?

A summary of the advantages and disadvantages of each device are listed in Table 6.17.

What are the resultant design implications of the study?

Both waist and bar mounted accelerometers can be used to monitor performance. High absolute validity is achieved when “simple” variables are calculated (do not require integration or a combination of variables). When calculating more “complex” variables that require integration (i.e velocity) and a combination of variables (i.e power), the high relative validity indicates that performance can be ranked and/or the time at which the peak variable occurred identified. A waist mounted accelerometer is limited to linear exercises, whilst the location of a waist mounted accelerometer may disrupt increasingly complex movements in which the the bar is pulled towards the midline of the body. A bar mounted accelerometer would provide additional information regarding the bar trajectory to characterise more complex exercises if gyroscope technology was integrated. The attachment of the bar mounted accelerometer needs to be redesigned to reduce rotation so that a range of simple linear exercises can be monitored accurately and analysis is not limited to whole body movements in which the bar moves with the body.

A force platform provides accurate information when monitoring explosive movements and provides a method for determining the force generated by the lower body which a bar or waist mounted accelerometer would not. A force platform would therefore be suited to monitoring more “complex” exercises that are highly explosive in which the bar and body move independently. The differences between the force platform and video is attributed to the fact that the force platform predominantly detects the performance variables generated by the whole body. In order for the movement of the body and bar to be monitored during complex exercises, a bar mounted system (with gyroscope technology) and force platform is required.

System	Summary
Force platform	• Low sig values and high correlation to video data for explosive movements (squat jump), high absolute validity exists. • High relative validity when determining the time to peak variable and subject ranking. • Provides accurate whole body analysis for bar and body movement. • Unaffected by rotation of the bar. • Easy identification of each rep. • Limited to explosive movements. • Has the highest percentage difference range at all analysis stages and least absolute validity when compared to video analysis but this is due to the force platform measuring the movement of the system mass (bar and body) rather than each in isolation. • Force platform still provides the most accurate information regarding whole body movement. • Zero velocity required at the start of each rep. • No information regarding bar trajectory when independent of the body. • Not currently suited to a gym based environment.
Bar mounted accelerometer	• Low sig values and high correlation to video data, high absolute validity exists. • High relative validity when determining the time to peak variable and subject ranking. • Can be used to monitor independent movement of the bar which widens the range of exercises that could be monitored. • Bar attachment needs to be secured to prevent device rotation. • Is affected by rotation of the bar due to the movement. • Zero velocity required at the start of each rep to achieve absolute validity.
Waist mounted accelerometer	• Low sig values and high correlation to video data, high absolute validity exists. • High relative validity when determining the time to peak variable and subject ranking. • Unaffected by rotation of the bar. • Lower absolute validity when monitoring more explosive movements, waist attachment must reduce or prevent added vibration during drive and landing phase. • Can only provide kinetic and kinematic data for the body not the bar. • Only suited to exercises where the bar does not move independently of the body. • Zero velocity required at the start of each rep to achieve absolute validity. • Affected by flexion of the spine. • Location of the device may disrupt effective execution of complex exercises. • Increased rotation during explosive movements. • No information regarding bar trajectory.

Table 6.15 Summary of the force platform, bar node and waist node advantages and disadvantages

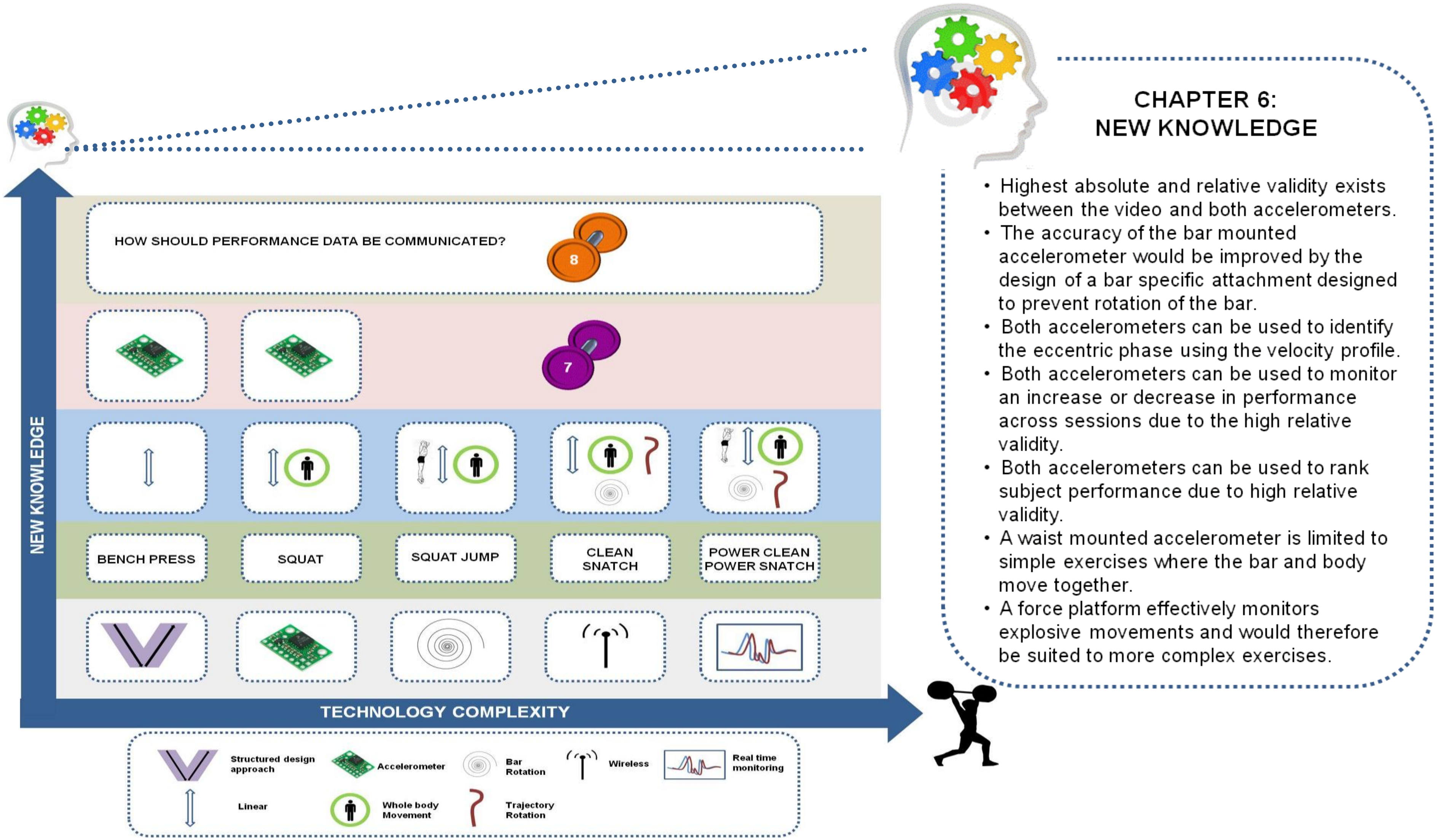
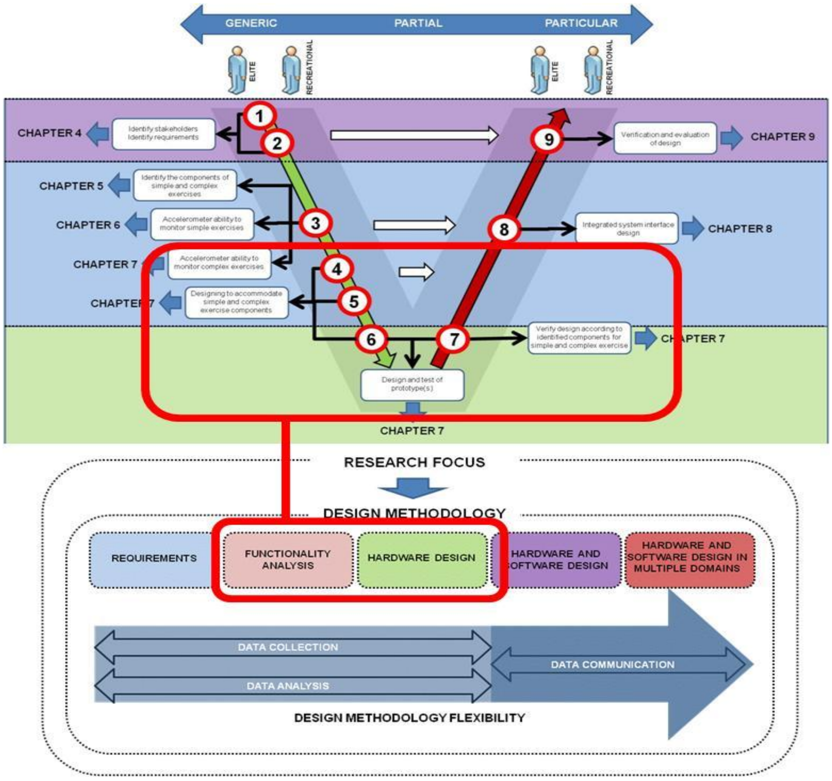


Figure 6.46 The identification of new knowledge acquired and core question findings; a simple tri-axis accelerometer is suitable for monitoring linear exercises such as the bench press or squat providing rotation is prevented through attachment design.



Chapter 7

7.0 Designing a system to monitor elite performance

TARGET OBJECTIVE:

Combine the most appropriate forms of technology to develop a combined system that supports the analysis of elite performance in the resistance training domain.

TARGET RESEARCH QUESTIONS:

- *How can the effects of rotation be minimised to improve the analysis of complex exercises?*
- *Which monitoring methods should be combined to increase performance knowledge gained and system validity of an elite based system?*

7.1 Introduction

The methodology proposed in Chapter 2 is centred around the iterative nature of the "Vee" model. The framework encourages decomposition of all the elements within the design domain to ensure that every design requirement can be derived from a user requirement. Therefore, in order to generate a full set of system requirements for an elite based system, the user requirements identified in Chapter 4 and testing results obtained from Chapters 5-6 were revisited to ensure each system requirement could be attributed to a need. The main aim of this chapter is to support the design phase in a structured manner that combines the user requirements and functional requirements derived from the testing in Chapters 5 and 6.

7.2 Evaluating the user and testing requirements

The testing conducted in Chapter 4 has outlined a number of user requirements. These user requirements form the basis of the subsequent testing and functionality analysis conducted in Chapters 5 and 6. Using the combined methodology, outlined in Chapter 2, testing was broken down into evaluating the performance of subsystems, resulting in an analysis of simple and complex exercises. Further decomposition identified that as the level of exercise complexity increased (i.e. from linear movements such as the bench press or squat to multi-planar movements such as the power clean or snatch) the number of key components and level of technology sophistication required to effectively monitor performance increased. An overview of the user requirements derived from Chapter 4 and the resultant functionality analysis conducted is presented in Figure 7.1. Functionality analysis conducted in Chapters 5 and 6 identified the following testing requirements:

- Chapter 5: The key components of the simplest exercises involved a linear trajectory and simultaneous bar and body movement. The key components of complex exercises involved non-linear trajectories, independent bar and body movement and bar and trajectory rotation. Therefore force platform technology is required to monitor body movement whilst a gyroscope is required to account for the rotation of the bar and monitor the independent bar movement.
- Chapter 6 Case study 1: Started at a low level of simplicity (analysis of the squat), monitoring linear movement in which the bar and body moved together. The results suggested that a simple tri-axial accelerometer could be used to monitor simple exercises providing the bar attachment was improved to reduce device rotation relative to the bar.

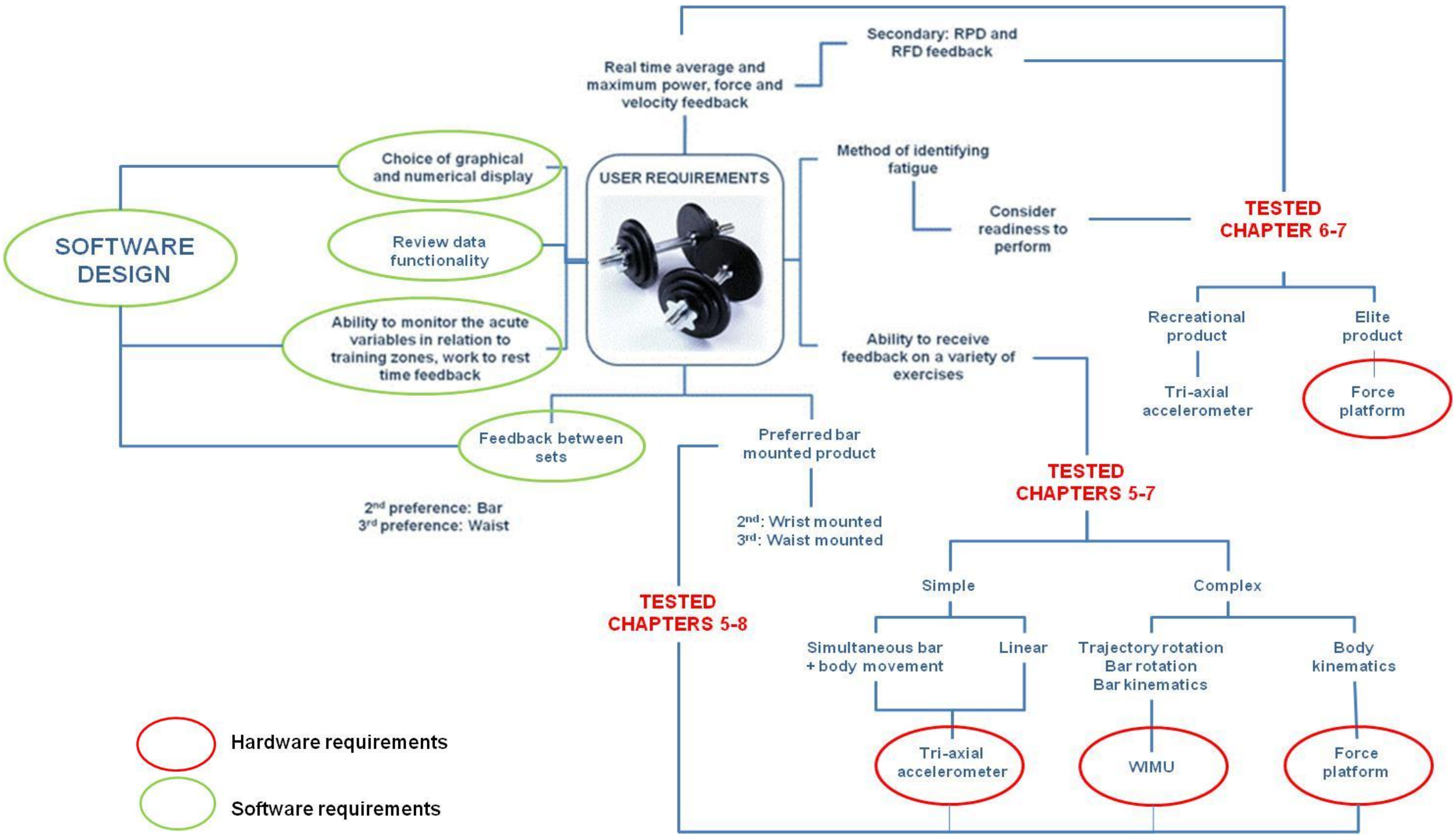
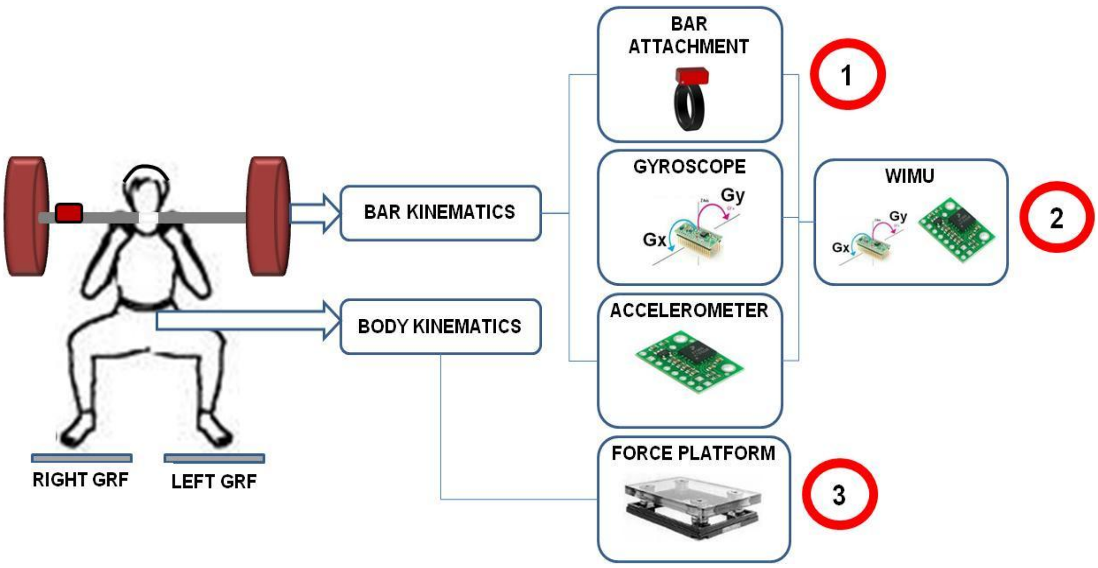


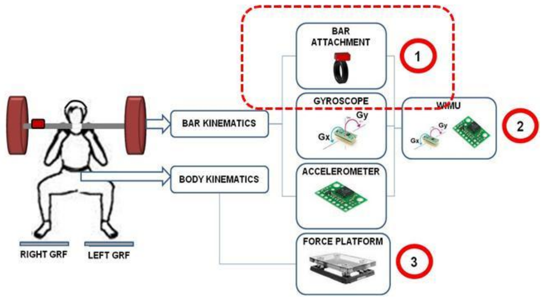
Figure 7.1 An overview of the user requirements identified in Chapter 4, the functionality analysis conducted to target the user requirements and the resultant design requirements.

- Chapter 6 Case study 2: Investigated the ability to monitor dynamic jump performance (a more complex exercise) using a waist mounted tri-axial accelerometer. The squat jump is a slightly more complex exercise but one which still required linear movement and aligned movement of body and bar. The results indicated that a simple tri-axial accelerometer could provide relevant kinematic data for linear exercises. At an elite level, additional performance data is required that cannot be determined using an accelerometer. For example, two force platforms (one for each leg) would be required to monitor the equality of force generated and differences between the left and right leg which could indicate weaknesses and/or injury. Uneven distribution of weight during a lift could result in serious injury which may hinder elite performance significantly, particularly during explosive movements (for which force platform analysis is most suitable). As a result of the decomposed testing, several design requirements were identified (illustrated in Figure 7.2). The design and development of each element is documented in this Chapter.



1. **A need to investigate the extent of device rotation to design a bar attachment that can prevent such rotation.**
2. **A need to combine accelerometer and gyroscope technology (WIMU development) to account for bar and trajectory rotation**
3. **A need to combine force platform technology with the accelerometer and gyroscope to fully monitor complex exercises in which bar and body move independently.**

Figure 7.2 The resultant main hardware design requirements identified using functionality analysis to design a system suitable for elite monitoring within a gym environment.



7.3 Device rotation

The results from Chapter 5 identified two types of rotation, bar rotation and trajectory rotation caused by non-linear lifts (see Chapter 5 Section 5.4). Both bar and trajectory rotation can be attributed to the technique required to execute the lift and therefore cannot be prevented. However, it is suggested that rotation of the device due to "slipping", (as illustrated in Figure 7.3) during a linear lift could easily result in erroneous data. To minimise the amount of correction, rotation can be minimised by redesigning the prototype attachment that secures the accelerometer to the bar.

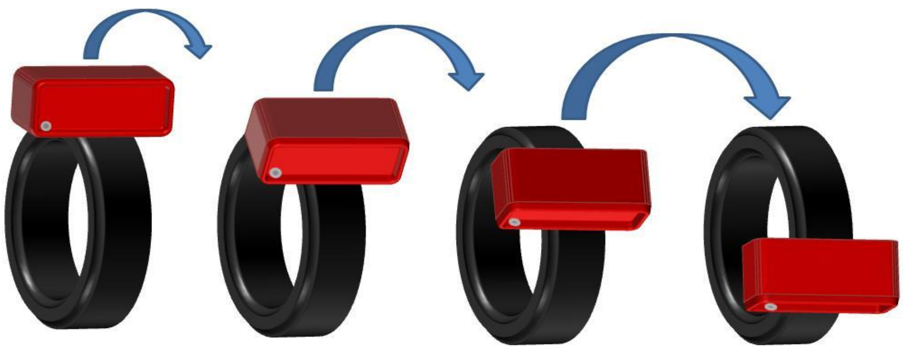


Figure 7.3 Representation of device rotation due to ineffective bar attachment design.

7.3.1 Case Study 1: Investigating the effect of device rotation

A pilot study was conducted to investigate whether "slipping" and rotation of the device was likely to occur during the execution of simple exercises which would be amplified further during complex exercises. One subject was asked to perform 3 sets of 5 squats. The subject was asked to attach the same prototype used in Chapter 6 to a 20kg bar, no instructions were given to the subject regarding the tightness of the strap or device orientation. The aim was to investigate how a user may interact with the current prototype and the result it would have on the accelerometer output. An example of an xyz axis squat set in which slipping of the device did not occur (A) and acceleration and vector profiles derived from the final squat set in which slipping of the device did occur (B and C), is presented in Figure 7.4.

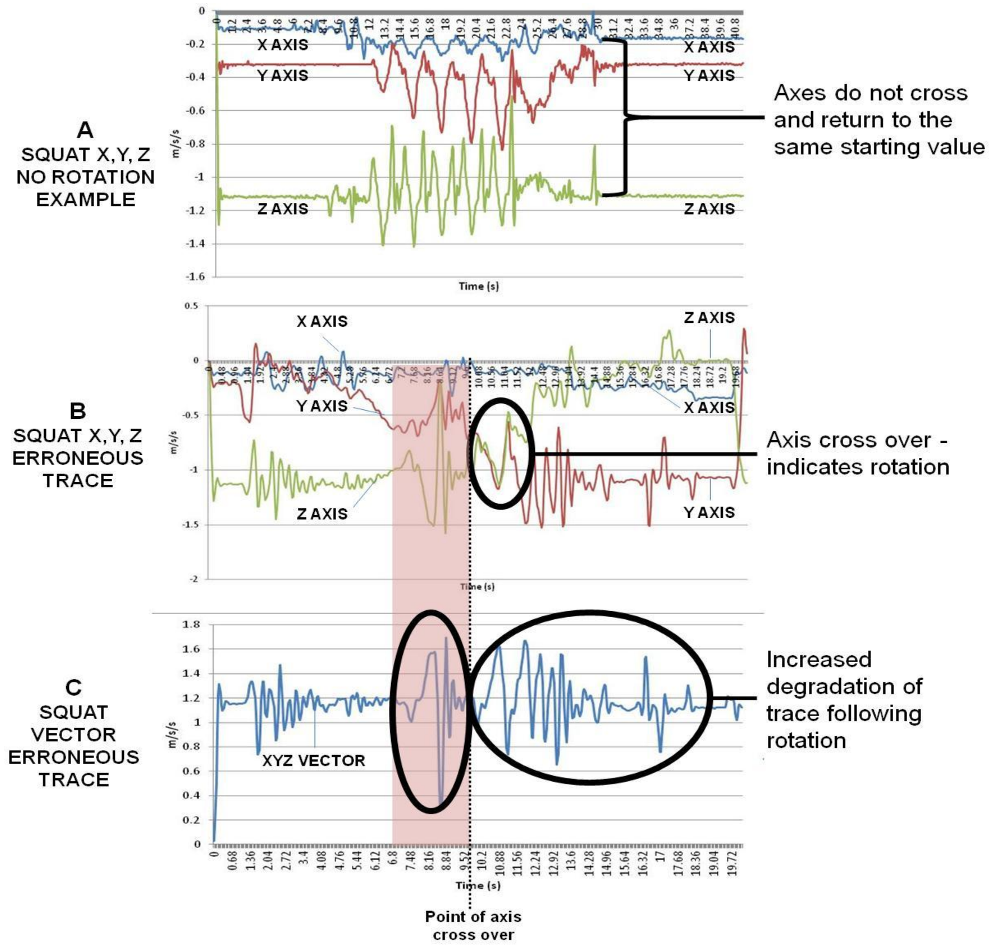


Figure 7.4 An example of the acceleration in all three axes experienced by an accelerometer during a squat set in which slipping of the device did not occur (A) and acceleration and vector profiles derived from the final squat set in which slipping of the device did occur(B,C).

The degradation of the xyz axis acceleration profile (B and C) in comparison to the example without rotation (A) suggests that accuracy of the data and ability to identify each rep is greatly affected by slipping of the device. The results indicate that rotation of the accelerometer occurred at the point of axis cross over (B). The first squat is identified in the trace (shaded column), however, following the cross over point, the signal does not exhibit the typical squat trace identified in Chapters 5 and 6. Therefore, slipping of the device due to insufficient tightening can dramatically reduce the accuracy of the accelerometer output. The pilot study clarified the need to prevent the rotational slipping of the device through redesign of the bar attachment.

7.3.2 Design generation of bar attachment

The initial stages of design generation required re-iteration of the design requirements. The elements listed provide a number of criteria against which the initial designs were evaluated. Each design was rated on a scale of 1 to 5, with 5 corresponding to fulfilment of the criterion. The total score was calculated to provide an overall rank. The initial design ideas are presented in Figure 7.5. The resultant ranking of each design using the identified criteria is listed in Table 7.1. The factors influencing the sensor attachment are also presented in Table 7.1

Criteria	Reason	A	B	C	D	E
Bar mounted	User requirements and testing indicated that a bar mounted design was most suitable.	5	5	5	5	5
Athlete	Device should not restrict athlete movement.	5	1	1	3	5
Range of exercises	Device should not limit the exercises that can be executed using the device.	5	1	1	2	5
Fixed location	WIMU must remain in a fixed position and not spin freely to enable rep identification and analysis.	1	1	4	1	5
PCB layout	The PCB board does not currently have any mounting features, inner packaging must hold and protect the board in place.	4	4	4	2	5
Antenna	The antenna must be accommodated and the casing must not affect the signal.	4	4	4	4	4
Preparation	Set up must not disrupt the session	3	2	3	3	4
Environment	Packaging must withstand unforeseen impacts in the gym environment.	4	4	2	2	4
Score		31	22	24	22	37

Table 7.1 Bar attachment design criteria and corresponding ranking of initial designs

The results indicate that the most suitable design is example E. The bayonet design (see Figure 7.5 (E)) allows the sensor to be attached to the inner bar that does not freely rotate. The subject does not have to alter grip or technique to execute any lifts and the range of exercises is not limited. The resultant design development using the bayonet example is documented in the following section.

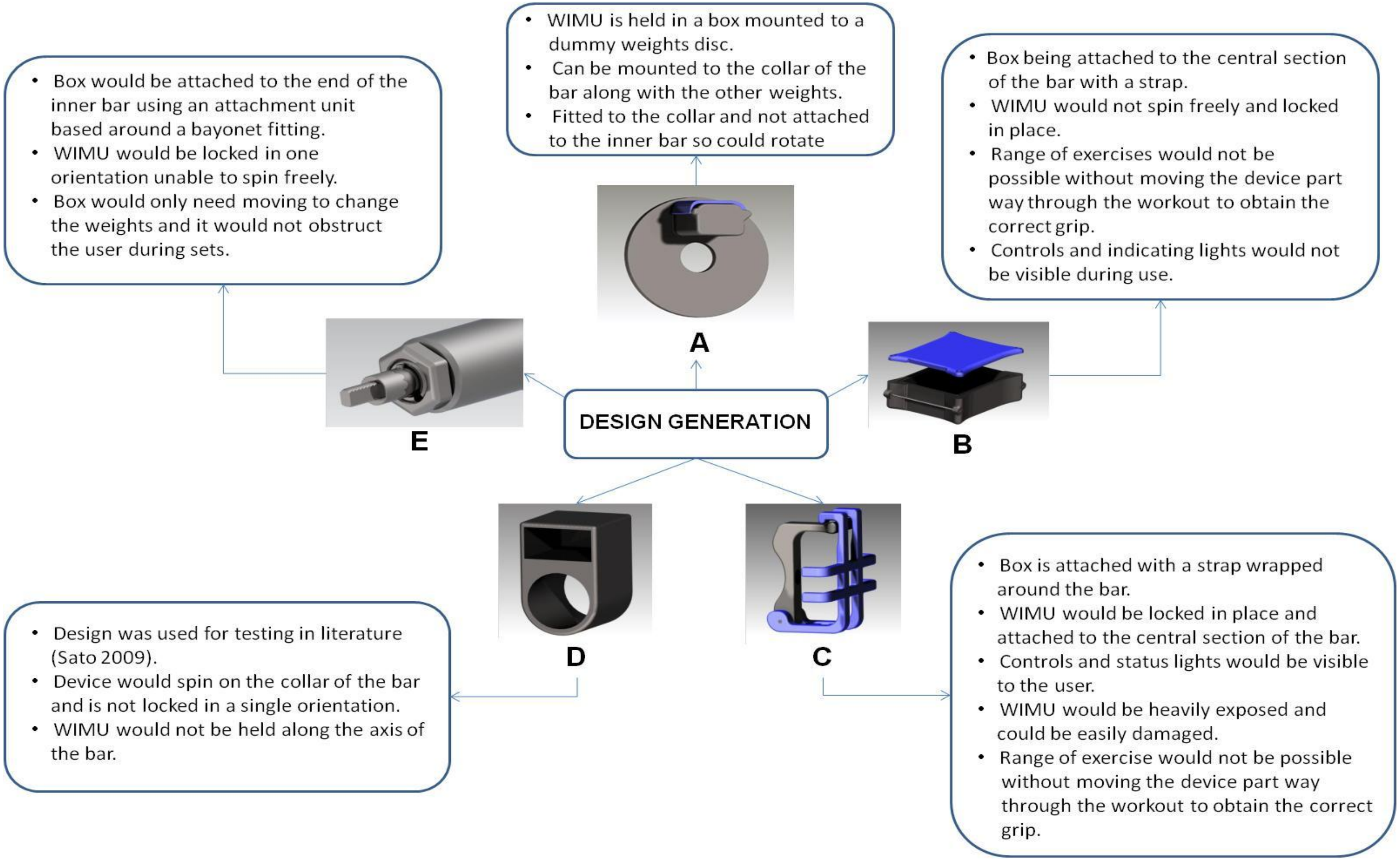


Figure 7.5 Initial generation of bar attachment design to reduce device rotation, in which design (E) was identified as the most suitable.

7.3.3 Development of a bayonet bar attachment

The bayonet design was generated further using Computer Aided Design (CAD). The design consisted of a circular box within which the WIMU was held securely in a new orientation (illustrated in Figure 7.6.) The new orientation meant that the z axis was placed along the bar, the x axis experienced (g) and detected movement in the vertical plane, whilst the y axis detected movement in the horizontal plane (forward and back). The cover of the box was threaded and held by a single screw to allow access to the sensor unit. The design focused on securing the existing circuit board (PCB) with no mounting features, therefore a foam block was included to secure the device and offer protection to the board when the bar was dropped during training.

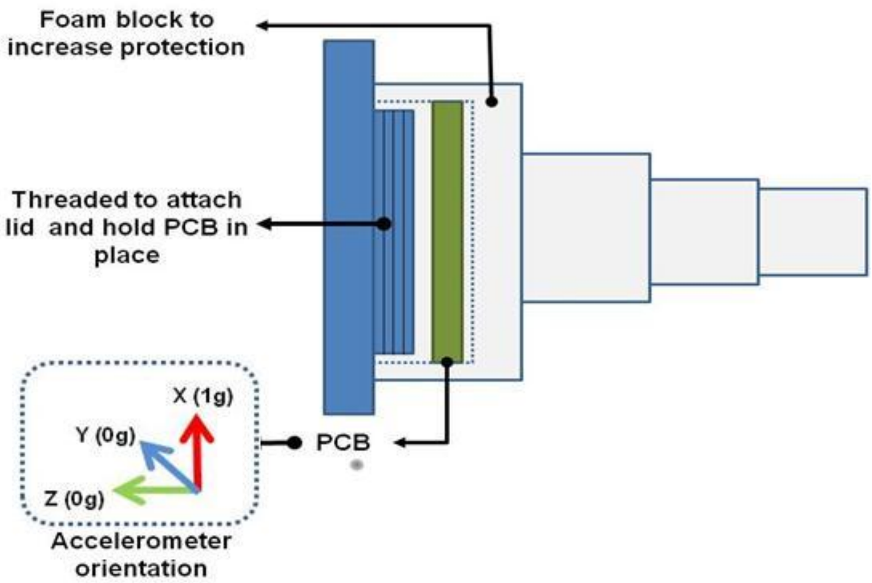


Figure 7.6 New orientation of the accelerometer using bayonet attachment.

To implement and test the design, a barbell required modification. The modification required removal of the bar end to allow the bayonet design to be attached as presented in Figure 7.7 (A). The box could then be detached from the weight bar allowing the pin and box to remain as a single unit, as demonstrated in Figure 7.7 (B). The box was designed with larger diameter than that of the collar of the bar to reduce the risk of weight discs being added to the bar whilst the device was still attached to the bar (preventing potential damage to the WIMU circuit board). The prototype design was manufactured from nylon and shaped using a lathe. Secondary machining operations were achieved using a milling machine. The manufactured prototype is presented in Figure 7.8. Detailed drawings of the bayonet design are presented in Appendix B.

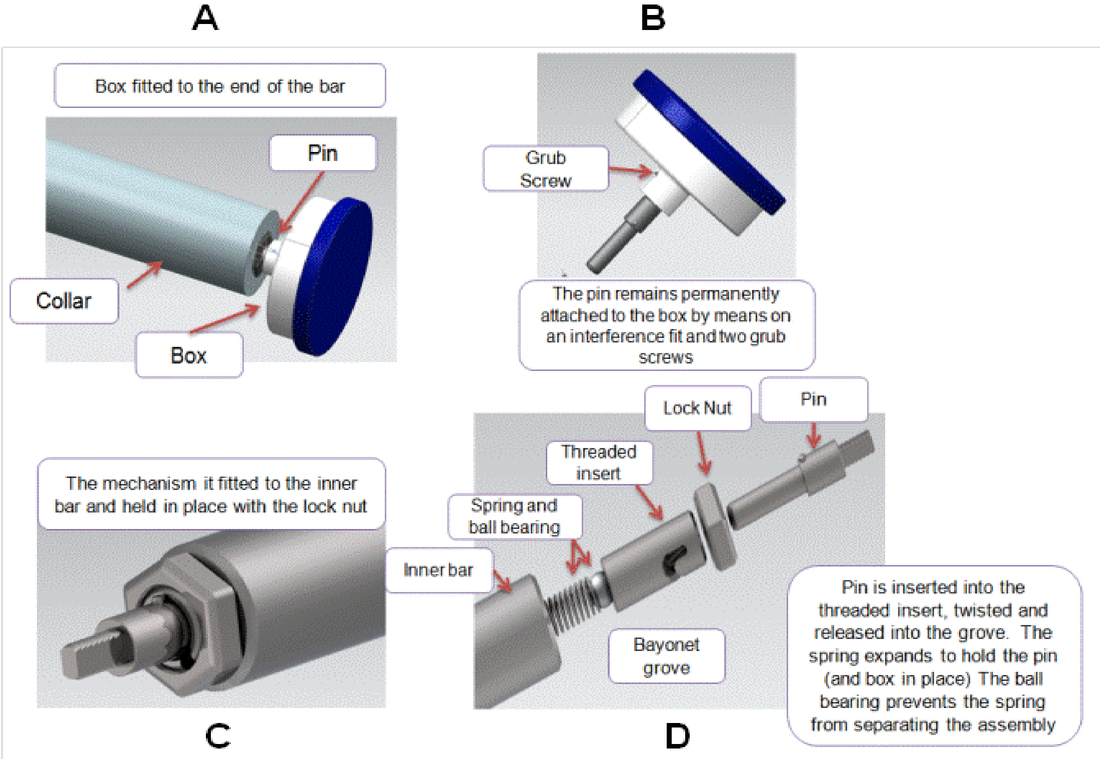


Figure 7.8 Further development of the bayonet design using Computer Aided Design (CAD).

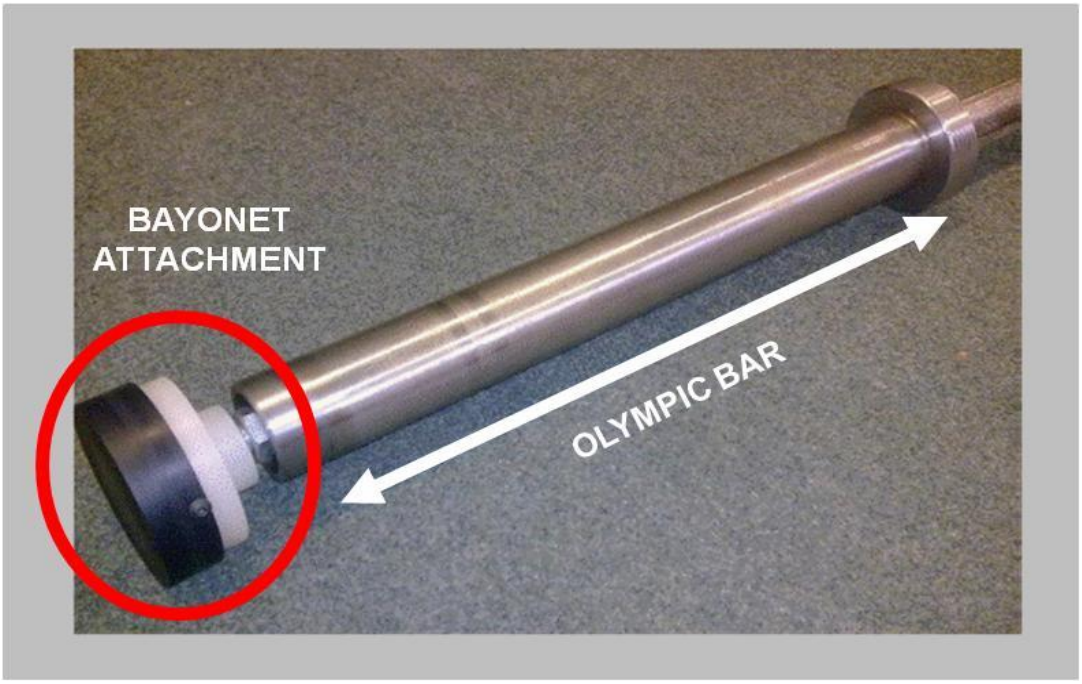
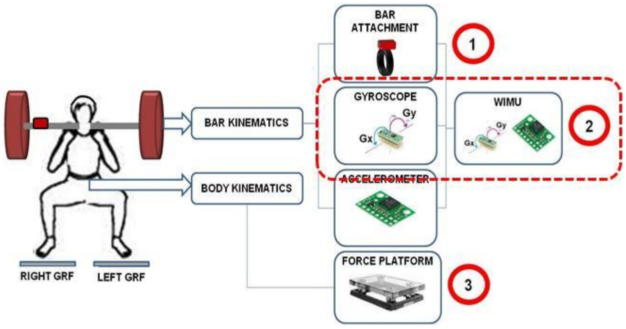


Figure 7.7 Manufactured prototype of bayonet bar attachment design (Gordon et al 2011)



7.4 Development of a Wireless Inertial Measurement Unit (WIMU)

Trajectory rotation is a fundamental aspect of the more complex exercises such as the power clean and power snatch. As identified in Chapter 5, a simple tri-axial accelerometer is affected by rotation and significantly reduces the accuracy of the derived acceleration profiles (correlation between the WIMU and accelerometer decreases from (0.862**) for a simple exercise to (0.175) for a complex exercise. Therefore, more advanced technology is required to account for the rotation during a complex lift. During complex exercises, the bar trajectory and nature of the lift causes bar rotation that cannot be eliminated. The results from Chapter 5 identified that rotation of the bar was a fundamental component of the power clean and power snatch, as illustrated in Figure 7.9.

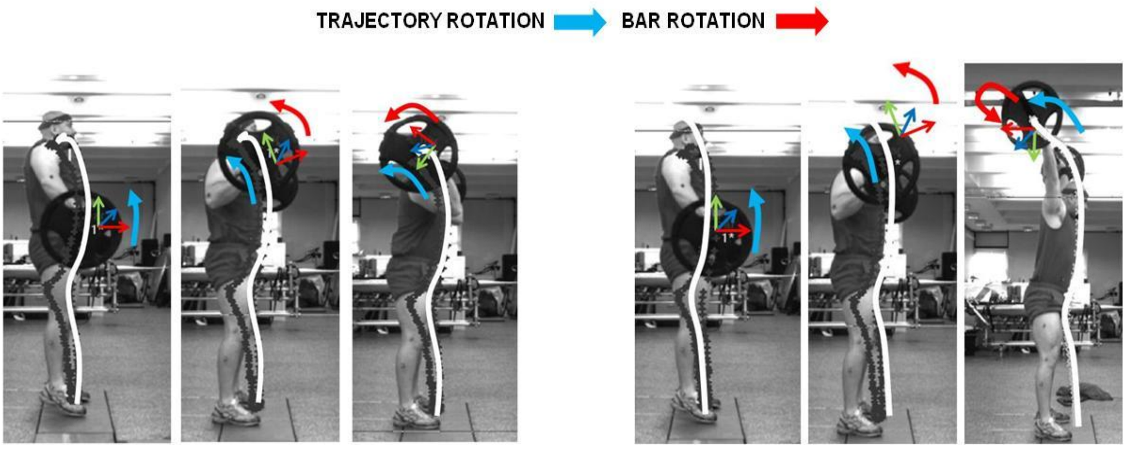


Figure 7.9 Bar and trajectory rotation present in both power clean and power snatch execution.

A combination of the device slipping, bar and trajectory rotation can dramatically reduce the accuracy of the accelerometer output. Therefore, in order to monitor complex exercises in which rotation of the bar is a key component, both the attachment of the device and integration of a gyroscope to form a wireless inertial measurement unit (WIMU) is required. The following section details the methods used to integrate a gyroscope and create a WIMU. As discussed in Chapter 3, a WIMU combines a single unit tri-axis accelerometer and two dual-axis gyroscopes to measure acceleration in three axes and angular velocity in three axes. The algorithms developed in this chapter have to be embedded in the developed product to allow real time data analysis.

7.4.1 Wireless Inertial Measurement Unit (WIMU)

A WIMU consists of three orthogonal MEMS accelerometers to measure acceleration in 3 axes and a tri-axis MEMS gyroscope to measure angular velocity in three axes (Woodman 2007). The accelerations measured in the local axis (i.e. body frame x′, y′, z′) have to be translated to a set of global axes (X, Y, Z), allowing for compensation of the earth's gravitational field. A sensor aligned with the global axes compared to a misaligned sensor (i.e. local frames x′, y′, z′, at angles β, α and φ to the global X, Y, Z) is presented in Figure 7.10 (a) and (b). As explained in Chapter 3, when stationary, the sensor orientation can be determined using the projection of the gravity vector detected by the accelerometers. When accelerating, the sensor orientation has to be derived from the angular velocity measured by a tri-axis gyroscope aligned with the x′, y′, z′ axes to detect rotation. Once the orientation is known, accelerations can be projected onto the global axes through a transformation matrix.

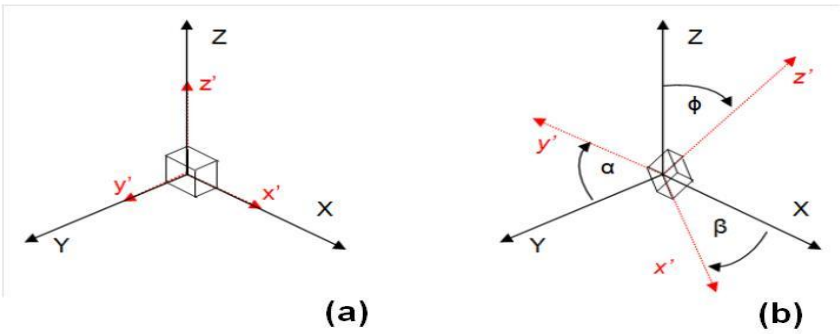


Figure 7.10 Sensor body axes aligned with global axes(a) and Sensor body axes not aligned with global axes (b).

7.4.2 2D Transformation matrix

As discussed in Chapter 3, a 3D transformation matrix can be used to determine the initial orientation. However, by fixing the x axis to be aligned with the bar (see Figures 7.7 and 7.8), a 2D transformation matrix should be sufficient to reduce both the complexity of the transformation and the associated processing time (see Figure 7.11).

An overview of the 3D transformation matrix first discussed in Chapter 3 and corresponding 2D transformation is presented in Figure 7.11.

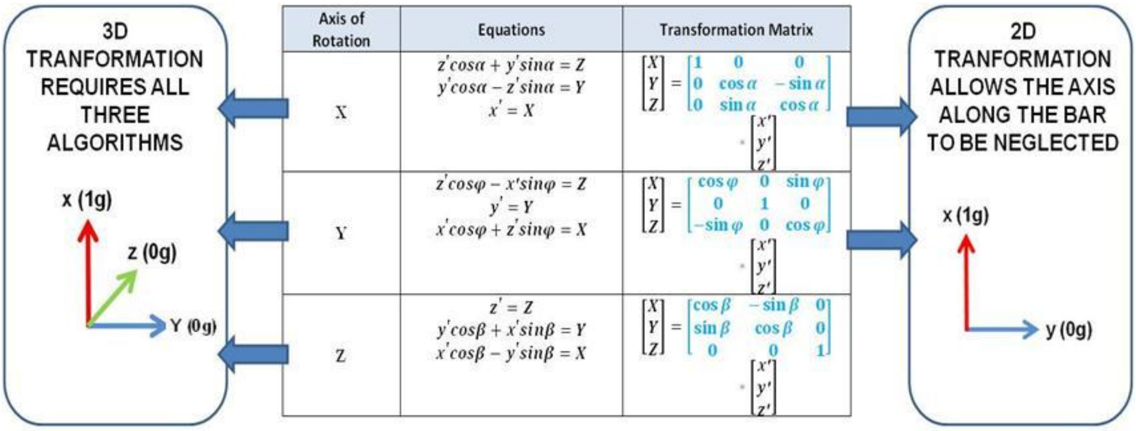


Figure 7.11 Overview of the 3D and 2D transformation matrices required to calculate and correct for the deviations from the global frame.

The initial orientation of the bar can be determined using the correction methods demonstrated in Table 7.2. These methods can be integrated to calculate the initial device orientation from which the subsequent angular rotation due to bar movement can be derived. The application of the 2D transformation rather than the 3D transformation, simplifies the analysis process significantly, since otherwise the initial angles have to be determined by solving the inverse of the matrix listed in Figure 7.11. In addition, the restriction of the movement of the accelerometer axis along the bar via the attachment design ensures that the rotation effect is minimised.

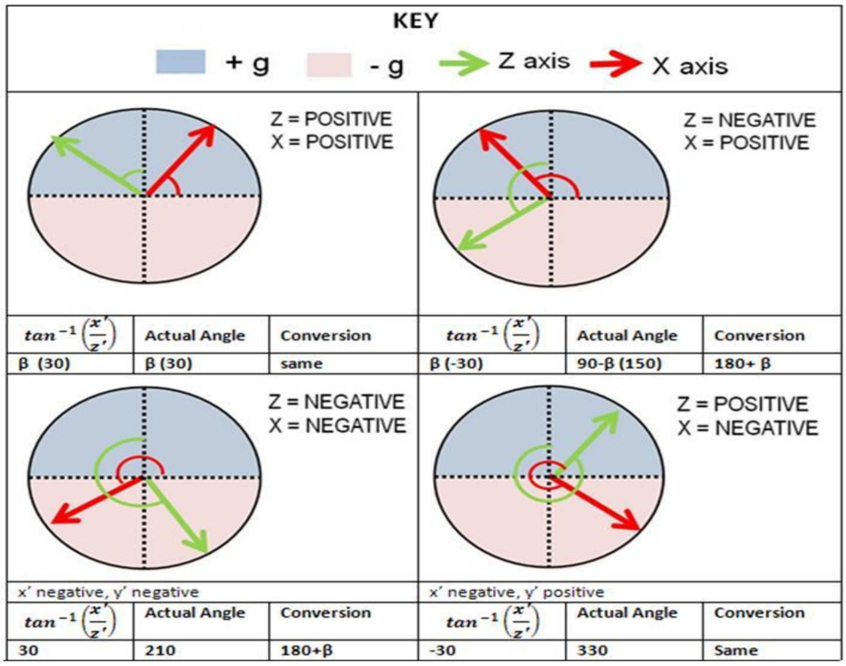


Table 7.2 Correction methods used to account for >90 degree deviation when using the 2D transformation matrix.

An overview of the processing required to collect accurate data using a WIMU is presented in Figure 7.12. The gyroscope and accelerometer devices must be calibrated and filtered to increase the accuracy of the WIMU data. The calibration procedure for the accelerometer and gyroscope is documented in Appendix C. As described in Chapters 5 and 6, a Butterworth filter was used to reduce the effect of noise in the accelerometer data. A moving mode filter was used to smooth the gyroscope data (De Levie 2004). The individual reps are identified and the initial angle determined (θ_i). The gyroscope angular rotation data is then integrated with the acceleration data to determine the final angles of the WIMU (θ_f). The original angles are re-aligned to match the angles derived using the gyroscope and the accelerations are transformed to the global frame (X, Y, Z).

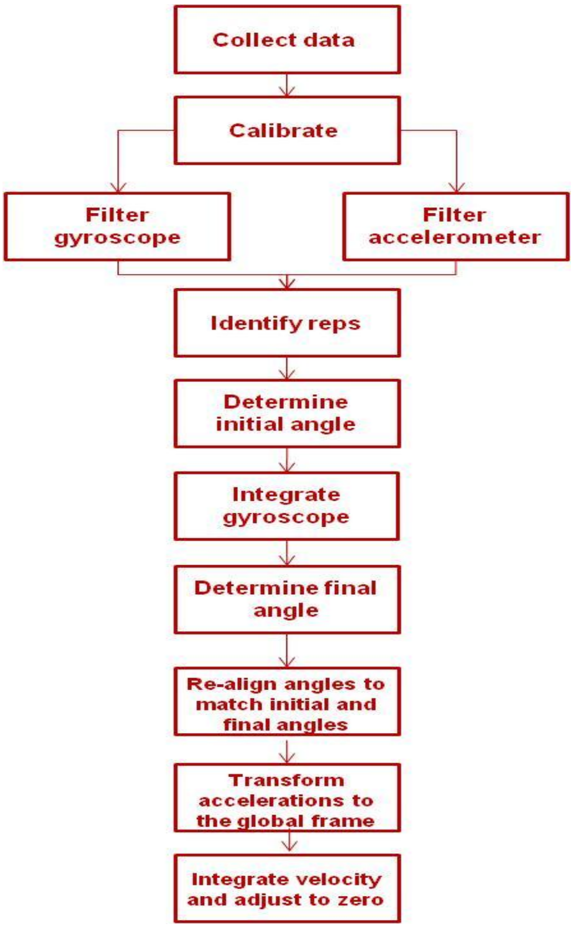


Figure 7.12 Processing steps required to derive kinematic data from a WIMU.

7.4.3 Case study 2: Validation testing of WIMU and bar attachment

To investigate efficacy of the new WIMU ability to monitor simple and complex exercises, a pilot study was conducted. Two athletes were monitored one recreational and one elite using video, force platform and WIMU technology. Each performed two sets of three cleans to investigate the following:

- Whether the bayonet bar attachment affected the wireless signal strength.
- Whether the bayonet bar attachment minimised device rotation.
- Whether the WIMU increased the validity of bar kinematic data for complex rotational exercises.
- Whether differences in technique could be identified using WIMU bar kinematic data.

The clean exercise involves both bar and trajectory rotation. The recreational subject (subject A) lifted a 20kg Olympic bar, whilst the elite subject (subject B) lifted 60kg. The recreational subject required support benches to lift the bar slightly off the ground to ease execution. The processing steps identified in Figure 7.12 were followed to analyse the WIMU data. This method was reliant upon the ability to identify and separate each rep manually. The 2D transformation matrix was used to determine the initial and final angles for each rep. Each rep was analysed up to and including the catch phase.

7.4.3.1 WIMU testing results

No loss of data was experienced during the study, indicating that the ability of the sensor to transmit wirelessly was not affected by the new bar attachment. The results from Chapter 6 indicate that error is propagated as the integration of the data increases, therefore, the calculation of velocity and velocity dependent parameters (such as power) are more prone to error. As discussed in Chapter 3, Section 3.5.4, the ability to produce power is particularly important at an elite level and velocity is required to determine power. The WIMU testing therefore focused upon the ability to derive velocity and resultant power. Example velocity profiles derived from the recreational and elite subjects are presented in Figures 7.13 and 7.14 respectively. Pearson's correlation coefficient was calculated for each recreational and elite clean velocity profile to determine the mean level of correlation between the video, force platform and WIMU derived velocity profiles (as conducted in Chapter 5). The results are presented in Table 7.3. The closer the correlation value is to 1, the higher the correlation between each system (video, force platform and WIMU).

Subject	Compared profiles	Pearson's correlation coefficient	Significant difference
Recreational	Video velocity v FP velocity	0.414	Yes
	Video velocity v WIMU velocity	0.942**	No
	WIMU velocity v FP velocity	0.417	Yes
Elite	Video velocity v FP velocity	0.675	No
	Video velocity v WIMU velocity	0.822**	No
	WIMU velocity v FP velocity	0.632	No

Table 7.3 Correlation between the recreational and elite clean velocity profiles derived from each monitoring system (* = sig at the 0.05 level, ** = sig at the 0.01 level)

The results presented in Table 7.3 indicate that high correlation exists at the 0.01 level between the video and WIMU derived velocity profiles for both the recreational (0.942**) and elite subject (0.822**). Significant difference does not exist between the video and WIMU velocity profiles. This is in contrast to the results discussed in Chapter 5 Sections 5.4.3, in which the mean correlation between the video derived acceleration and simple tri-axis accelerometer (without gyroscopes) for the power clean and power snatch indicated that significant difference existed between the two systems (0.379).

Significant difference exists between the recreational velocity profiles derived from video and force platform (0.414) and WIMU and force platform (0.417). An example of the bar trajectory and resultant velocity profiles produced by the recreational subject is presented in Figure 7.13 (a) and (b). The results indicate that the derived force platform peak velocity (Figure 7.13 (a), (1.02 m/s)) occurs earlier (0.8 s rather than 0.92 s) and is significantly lower than the video (2.49 m/s) and WIMU (2.46 m/s) derived peak velocity (Figure 7.13 (b)). These data support the low correlation values listed in Table 7.3. However, once again, low correlation between the video and force platform is expected as the force platform measures whole body movement whilst the video analysis measures bar and body movement separately. The force platform data for the recreational subject suggest that peak velocity of the body occurred before peak velocity of the bar was reached (a difference of 0.12 s). This delay caused the subject to complete the remainder of the exercise using the upper body alone creating a loop in the trajectory (Figure 7.13 (b)). As discussed in Chapter 3 Section 3.5.1, the path of the bar should remain as close to the body as possible to allow the legs to drive the bar against gravity without straining the back. However, the bar trajectory and resultant velocity profile produced by the recreational subject indicates that the trajectory significantly deviated from the body and a large loop was performed resulting in one definitive velocity peak detected by each system.

An example of the bar trajectory and resultant velocity profiles produced by the elite subject is presented in Figure 7.14 (a) and (b). In contrast, significant difference does not exist between the elite velocity profiles derived from video and force platform (0.675) and WIMU and force platform (0.632). The results indicate that the elite and recreational velocity and power profiles differed greatly. The velocity profile produced by the elite subject (Figure 5.14 (b)) exhibits 2 distinct phases, indicating that the double knee bend technique was utilised (Stone et al 2006). The first (b1) and second pull phase (b2) of the clean is clearly visible. The first pull occurs as the bar is deadlifted in a linear fashion to the mid thigh. The subject then uses the double bend technique to drive the bar into the catch position, reducing the work done by the upper body. The difference in magnitude of the peak velocity derived from the force platform (1.47 m/s), video (2.62 m/s) and WIMU (3.00 m/s) is lower than that produced by the recreational subject whilst the delay between the force platform, video and WIMU peak velocity is reduced (0.04 s). These data support the higher correlation values between the video and force platform (0.675) and WIMU and force platform (0.632) derived velocity profiles in comparison to the recreational subject (0.414 and (0.417) respectively.

The reduced delay between the force platform derived velocity and video and WIMU derived peak velocity suggests that the elite subject was able move the bar linearly with the body to exert force generated from the body to the bar more efficiently, resulting in a higher peak velocity. The higher efficiency of the lift is characterised further by the trajectory which remains close to the midline of the body (Figure 5.14 (a) and (b)). Therefore, ineffective technique may be characterised by an increased time delay between the WIMU and force platform derived peak velocity and lack of a double peak in each profile. Such timing differences between the bar and body would not be possible using either monitoring system in isolation.

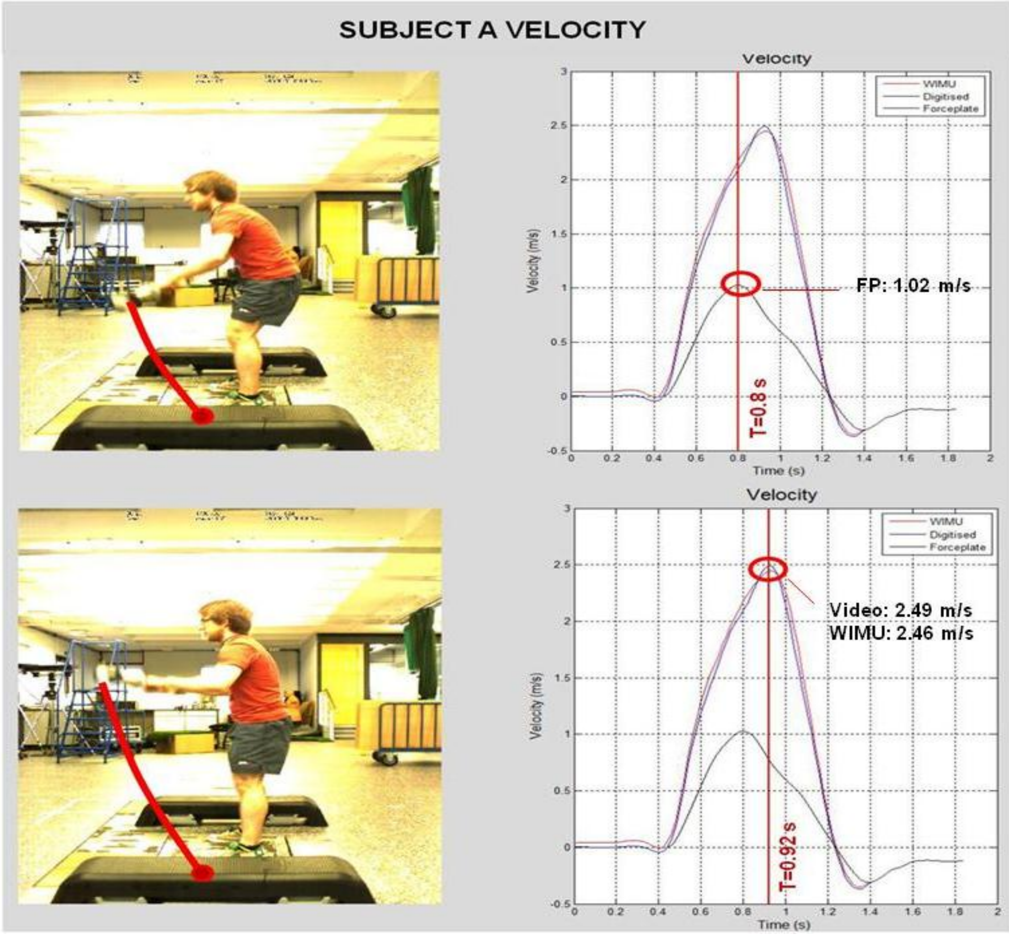


Figure 7.14 Recreational velocity profile during a clean indicating high correlation between the video and WIMU and a difference in velocity of the body detected by the force platform.

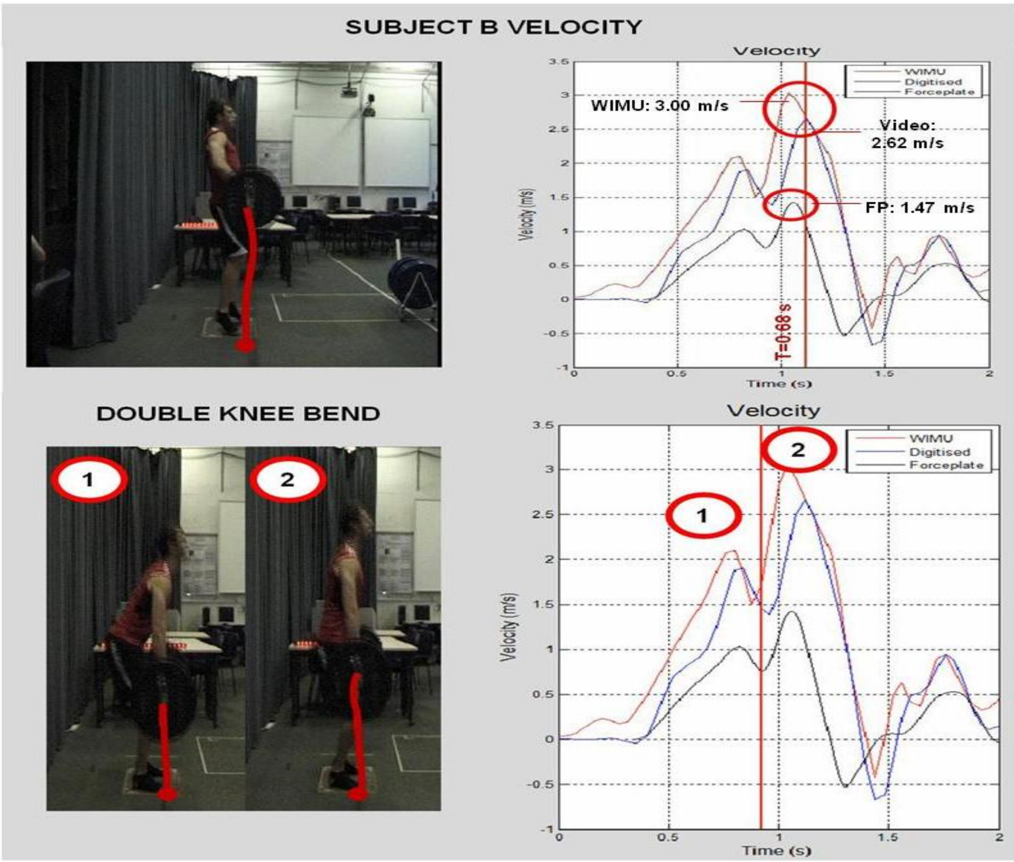


Figure 7.13 Elite velocity profile during a clean and identification of the double knee bend technique (1) first pull phase (2) second pull phase, present in the video, WIMU and force

7.4.3.2 Calculating power for complex exercises using WIMU data

There is much debate over the most relevant approach to determine power in weight training (Dugan et al 2004, Harris 2008). The methods of power calculation used in Chapter 6 investigated the calculation of power using two methods, one which included the system weight in the force calculation (PPSW) and one which excluded the system weight (PPNSW).

The results indicated that the time to peak was easier to identify using the PPNSW profile but the PPNSW profile provided the highest overall correlation. Including the system weight eliminated the possibility of a positive peak occurring during the negative phase of the squat exercise, preventing the inaccurate calculation of peak power during the eccentric phase. However, more complex exercises, such as the clean or snatch, do not have an initial eccentric phase and the bar does not move with body centre of mass. The kinematic behaviour of the bar does not match that of the body centre of mass and therefore cannot be characterised by the power derived from the force platform vertical GRF alone. There is a need to determine the amount of power exerted by the body and how this power is transferred to the bar to monitor accurately a complex exercise. For this need and analysis, a bar mounted system is essential.

7.4.3.2.1 Combined power calculation

Calculating the power generated by the body using the force platform and the power exerted on the bar using the WIMU can provide a *combined estimation of power*. Using this combined estimation may provide a method for determining the amount of power generated by the body in relation to the resultant power exerted on the bar as a measure of lifting efficiency. An illustration of the proposed combined power concept is presented in Figure 7.15.

The combined power value represents the maximum amount of power that would be produced if the total force generated by the whole body (detected by the force platform) was transferred to the bar when combined with the velocity of the bar (detected using the WIMU). The WIMU derived power (WIMU force x WIMU velocity) can be compared to the combined power (force platform force x WIMU velocity) to estimate the *efficiency* of the lift (see Figure 7.15). A WIMU derived power value less than the combined power value would indicate that force was not efficiently transferred from the whole body to the bar. A WIMU power value higher than the combined power value would indicate that the force generated by the whole body was fully transferred to the bar and an additional component of force was generated by the upper body to produce a higher power value. A WIMU value of a similar magnitude to the derived combined power value would indicate that a high proportion of the force produced by the lower body was transferred to the bar and the lift was therefore more efficient. This method of comparison could be used to distinguish between good (high transfer of whole body force to the bar to produce more power) and poor performance (where little force is generated or transferred from the whole body to the bar). The proposed combined power calculation involves the division of the WIMU power by the combined power value. It is proposed that the closer this value is to one, the higher the efficiency of the lift (as illustrated in Figure 7.15).

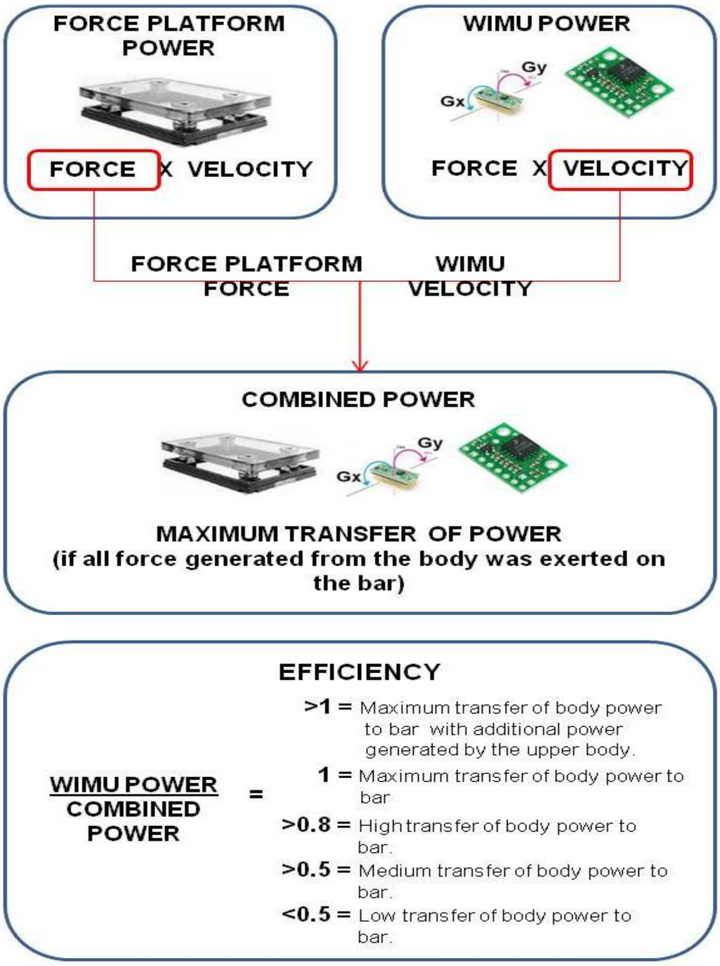


Figure 7.15 The calculation of "combined power" by multiplying the force platform data with the WIMU bar velocity.

The results from Chapters 5 and 6 also indicate that calculation of integration dependent variables such as velocity and power are prone to error. By combining the power calculated separately for the bar and body, the error present in the force platform derived power and WIMU derived power would be amplified further. Using the force platform to calculate the force component and multiplying this value with the derived bar velocity, provides a *combined power estimation* of higher accuracy. The force platform power, WIMU power and combined power were each calculated for the recreational and elite subject to identify whether the combined value provides additional information.

Example power profiles derived from the recreational and elite subjects are presented in Figures 7.16 and 7.17 respectively. Each method of analysis (video (762 W), force platform (1150 W), WIMU (1463 W) and combined power (1485 W)), (Figure 7.17 (a) and (b)), indicates that the elite subject produced significantly higher peak power values than the recreational subject ((video (173 W), force platform (237 W), WIMU (274 W) and combined power (542 W)) (Figure 7.16 (a) and (b)). The recreational profile indicates that the WIMU derived peak power occurred earlier (Figure 7.16 (a)) than the video, force platform or combined peak power (Figure 7.16 (b)). Alternatively, the WIMU peak power occurs at approximately the same time in the video, force platform, and combined peak power profile for the elite subject (Figure 7.17 (a)). However, the elite subject produced two peaks in the trace for combined power. The second peak is attributed to the elite subject exhibiting a flight and landing phase during the second pull of the clean (Figure 7.17 (b)). As discussed in Chapter 6, identification of the peak that corresponds to the actual peak power is a design requirement that needs to be accommodated in the software design as manual identification of the exercise rep in the early stages of design development may be required.

Pearson's correlation coefficient was calculated for each recreational and elite clean power profile to determine the mean level of correlation between the video, force platform and WIMU derived power profiles (as conducted in Chapter 5). The results are presented in Table 7.4. The closer the correlation value is to one, the higher the correlation between each system (video, force platform, WIMU).

Figure 7.17 Recreational power profiles calculated using several methods: WIMU, video and net force data in isolation and combining the force platform force and WIMU velocity.

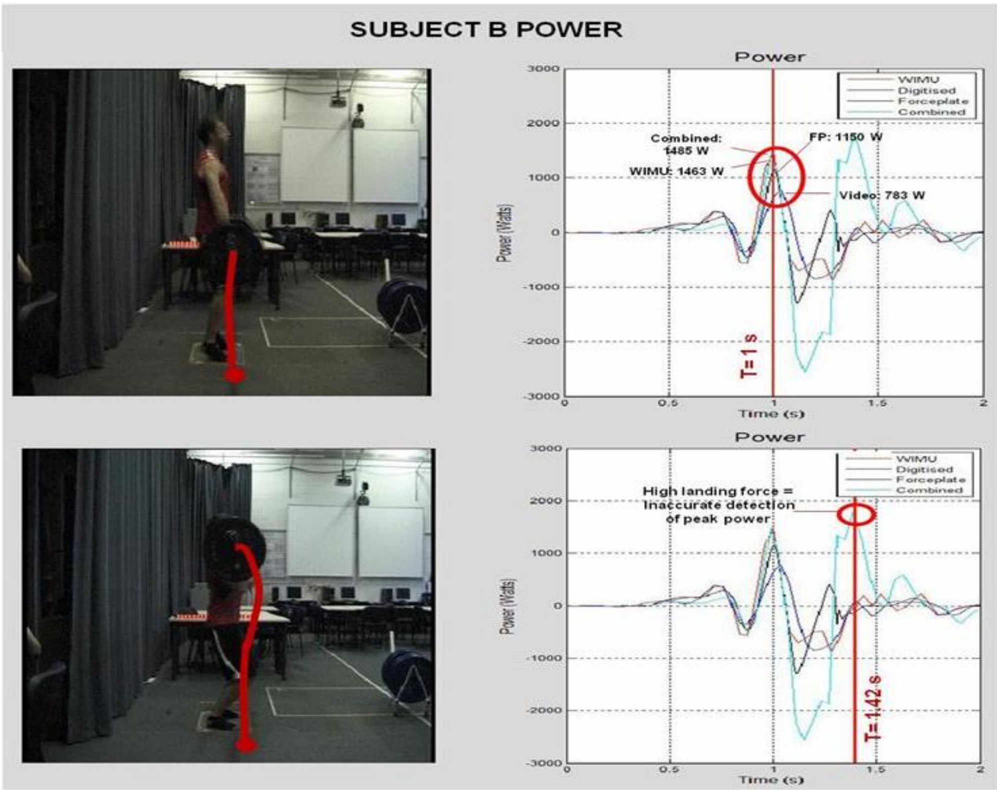


Figure 7.16 Elite power profiles calculated using several methods: WIMU, video and net force data in isolation and combining the force platform force and WIMU velocity.

Subject	Compared profiles	Pearson's correlation coefficient	Significant difference
Recreational	Video power v FP power	0.724*	No
	Video power v WIMU power	0.676	No
	WIMU power v FP power	0.711	No
	Combined power v video power	0.533	Yes
	Combined power v FP power	0.786*	No
	Combined power v WIMU power	0.632	No
Elite	Video power v FP power	0.813**	No
	Video power v WIMU power	0.857**	No
	WIMU power v FP power	0.901**	No
	Combined power v video power	0.645	No
	Combined power v FP power	0.686	No
	Combined power v WIMU power	0.712*	No

Table 7.4 Correlation between the recreational and elite clean power profiles derived from each monitoring system.

The results presented in Table 7.4 indicate that significant difference does not exist between the video and WIMU derived power profiles at the recreational (0.676) and elite level (0.833*). However, the correlation is lower than that between the video and WIMU derived velocity profiles at the recreational (0.942**) and elite level (0.822**). This can be attributed to the amplification of error through the combination of variables (force x velocity). The results contrast those produced in Chapter 5 Sections 5.4.3, in which the mean correlation between the video derived acceleration and simple tri-axis accelerometer (without gyroscopes) for the power clean and power snatch indicated that significant difference existed between the two systems (0.379).

The lowest correlation exists between the combined power and video derived power profiles for the recreational subject (0.533). The correlation between the combined power and WIMU derived power for the recreational subject (0.632) is lower than the correlation between the combined power and WIMU derived power for the elite subject (0.712*). This is supported by Figure 7.16 (a) and (b) in which the profiles do not exhibit the same synchronicity present in the elite power profiles (Figure 7.17 (a) and (b)). Lower correlation between the combined power and WIMU for the recreational subject may indicate that either significant force was produced by the upper body or that little force was transferred to the bar from the lower body to exert power. This cannot be determined without calculating the WIMU derived power to combined power ratio. This proposed *combined power estimation* ratio was calculated for six lifts, the results are presented in Table 7.5.

Subject	Lift	WIMU power (W)	Combined power	WIMU to combined power ratio	Efficiency
Recreational	Clean 1	274	542	0.51	Low/Med
	Clean 2	250	566	0.44	Low
	Clean 3	270	511	0.53	Low/Med
Elite	Clean 1	1463	1485	0.99	High
	Clean 2	1231	1760	0.70	Med
	Clean 3	1527	1593	0.96	High

Table 7.5 Estimation of the lift efficiency using the WIMU power to combined ratio.

The results indicate that the elite subject WIMU power values are much closer to the estimated "combined power" values resulting in higher efficiency values (ranging from 0.70 to 0.96). Using the suggested efficiency ranges (low, medium to high) the elite subject executed all three lifts with high to medium efficiency. In contrast, the recreational subject executed all three lifts with medium to low efficiency due to the significantly lower WIMU derived values when compared to the "combined power" values (ranging from 0.44 to 0.53). The low WIMU derived power values and high combined power values indicate that force generated by the whole body was not efficiently transferred to the bar. The results suggest that the difference between the bar mounted accelerometer and force platform data can be used to quantify the lifting efficiency for complex exercises. In order to do so, a combined system that consists of a bar mounted accelerometer and force platform is essential.

A summary of the results produced using a bar mounted accelerometer with gyroscope technology in comparison to those originally derived in Chapter 5, Section 5.4.3 using a simple tri-axis accelerometer to monitor complex exercises, is presented in Table 7.6. Overall the results suggest that a simple tri-axis accelerometer without gyroscopes is not suitable for monitoring complex exercises and that a WIMU is capable of monitoring complex exercises (correlation range between the video and WIMU increased from (0.175 - 0.582) to (0.676 - 0.942**)). Significant difference does exist between the force platform and WIMU velocity for the recreational subject (0.417), however this is supported by corresponding low correlation between the video and force platform derived velocity (0.414). The agreement between the video and WIMU derived velocity indicates that a low proportion of velocity was driven from the lower body and exerted on the bar. This is reflected further by the combined power estimation ratio which suggests that the lifting efficiency was low and little force or power was generated and transferred to the bar from the lower body. The significant looping of the bar trajectory (Figure 7.16 (a) and (b)) also suggests that the lift was inefficient. The bar kinematic data could aid distinction between elite and recreational analysis due to the looping present in the trajectory and ability to identify execution of the double knee bend technique (as identified in Figure 7.14 (b)). Using either the WIMU or force platform technology in isolation would not provide a wide range of information or data regarding lifting efficiency. Whether the power transfer ratio is higher for elite athletes would be an area for future investigation using the developed technology.

The ability to use both force platform and WIMU technology also allows the efficiency between the body and bar to be monitored using the time between peak variables. As discussed in Section 7.4.3.1, the time delay between peak variables (such as peak velocity) detected using the force platform and WIMU may indicate that the transition from the first pull to the second pull of a complex lift was not smooth or efficient. Determining optimal timing between the body and bar peak variables would provide invaluable data to monitor elite performance and would only be possible with a bar mounted WIMU and force platform integrated system.

Compared profiles	Simple tri-axis accelerometer correlation range	Sig. diff	WIMU velocity (accelerometers and gyroscopes)	Sig. diff	WIMU Power (accelerometers and gyroscopes)	Sig. diff
Video	0.175 - 0.582	Yes	0.822 – 0.942**	No	0.676 – 0.857**	No
Force platform	0.096- 0.034	Yes	0.417 – 0.632**	Yes	0.711 – 0.901**	No

Table 7.6 Summary of the improved correlation between video, force platform and accelerometer technology when gyroscopes are integrated.

Unequal force distribution may also affect the alignment of the bar preventing it from remaining parallel to the floor. Misalignment of the bar will be detected through analysis of the accelerometer axis monitoring movement along the bar. How this component changes during the execution of a lift could provide useful information regarding subject lean which may be enhanced further using force platform analysis in an integrated system. An example of a subject leaning significantly to the right during a squat is presented in Figure 7.18 (c). Example acceleration detected by the accelerometer x axis (along the bar) without lean (a) and with lean (b) is also illustrated

(Figure 7.18). The xyz acceleration trace in which the subject does not significantly lean to one side (a) indicates that the acceleration along the x axis does not significantly fluctuate (the x axis output lies within 0.05(g) of the initial orientation reading). In contrast, the xyz acceleration trace in which the subject does significantly lean to one side (b) indicates that the acceleration along the x axis does significantly fluctuate (the x axis output fluctuates between 0.1(g) and 0.3(g)). The fluctuation is synchronous with the z and y axes (the peaks occur at the same time) indicating that the bar is tilting consistently with each rep. Whether this tilt is attributed to unequal force distribution from the lower body or whether it is a result of poor upper body alignment can only be identified using a combined WIMU and double plate force platform system in which the right and left foot force production can be analysed separately. The development of a force platform to be combined with the WIMU in a gym environment is discussed in the following section.

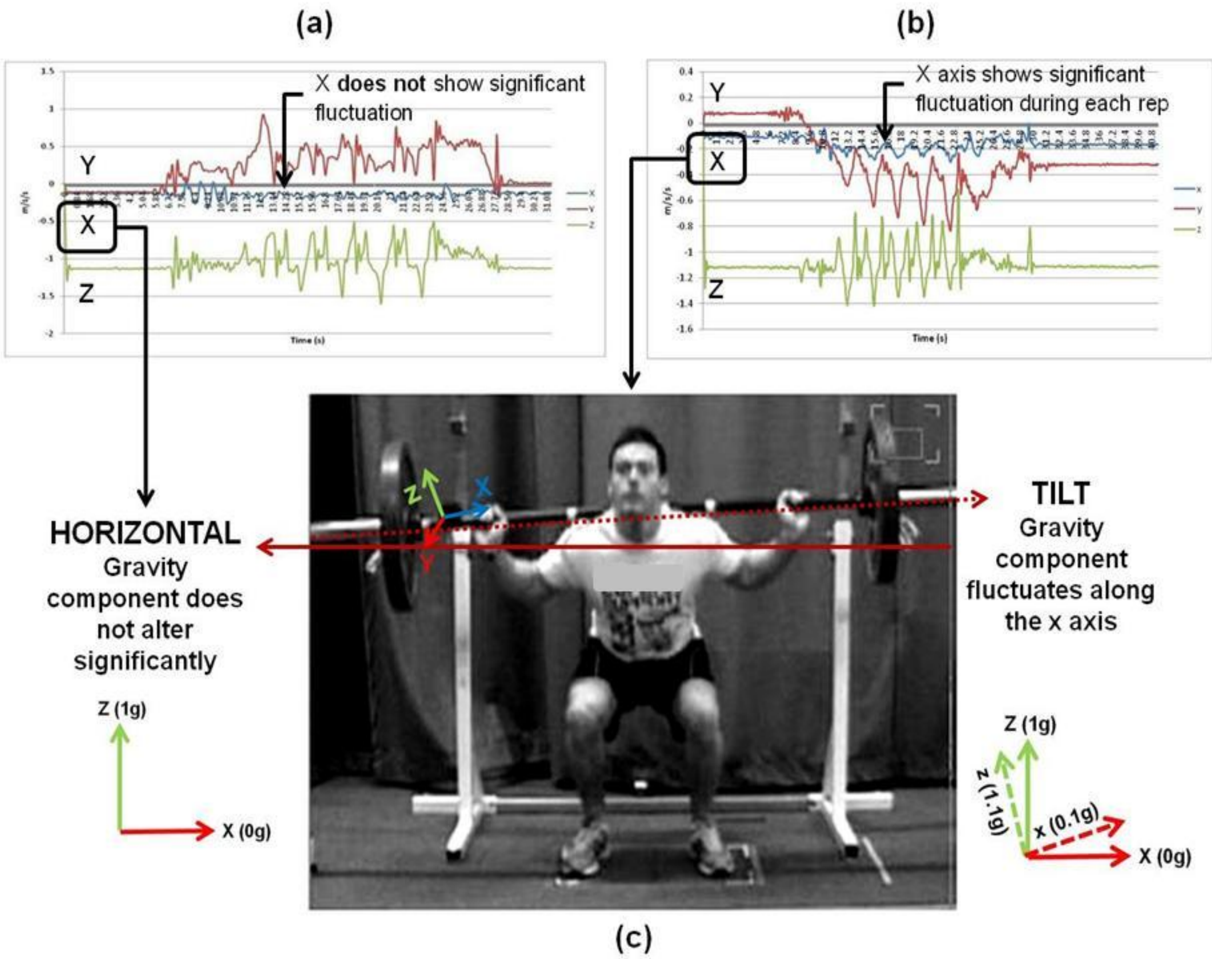
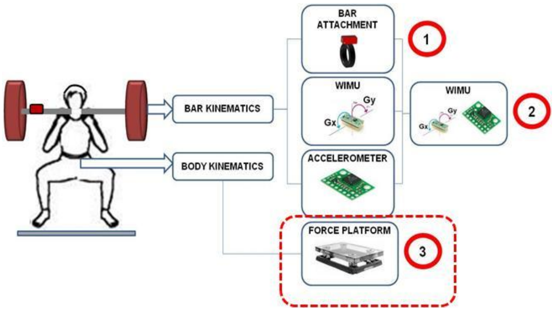


Figure 7.18 Example of subject lean during a squat and resultant identification in the acceleration trace placed along the bar (x axis).



7.5 Development of a force platform

As identified at the beginning of the Chapter and supported further by the results from Case study 2, a combination of WIMU and force platform technology would provide both bar and body kinematic data. Therefore it is suggested that to provide elite performance analysis both force platform and WIMU technology is required to fully analyse complex exercises at an elite level. A case study was conducted to determine whether two force platforms would be most suitable for a combined elite based performance monitoring system rather than one to investigate the difference between right and left leg force production.

7.5.1 Case study 3: Determining the value of double plate force platforms

An elite and recreational subject were instructed to place one foot on each plate to investigate whether there was a significant difference in force generation from each leg during the execution of the squat. The acceleration, velocity, force and power profiles were derived from the force platform to investigate whether significant difference existed between the recreational and elite profiles. It was hypothesised that significant difference between user experience and resultant acceleration, velocity and force profiles would enable identification of the elements that characterise good or bad performance.

The GRF bilateral differences between the left and right foot for the recreational and elite subject are illustrated in Figure 7.19 (a) and (b) and Figure 7.20 (a) and (b) respectively. The three distinct phases of the squat identified in Chapter 5 and 6 ((1) Negative peak as the subject contracts eccentrically and the bar is lowered, (2) Positive peak following the change in direction and concentric contraction as the work is done against gravity and (3) Rapid deceleration causing a final large negative peak) are present in the recreational (Figure 7.18 (a) and (b)) and elite squat (Figure 7.19 (a) and (b)).

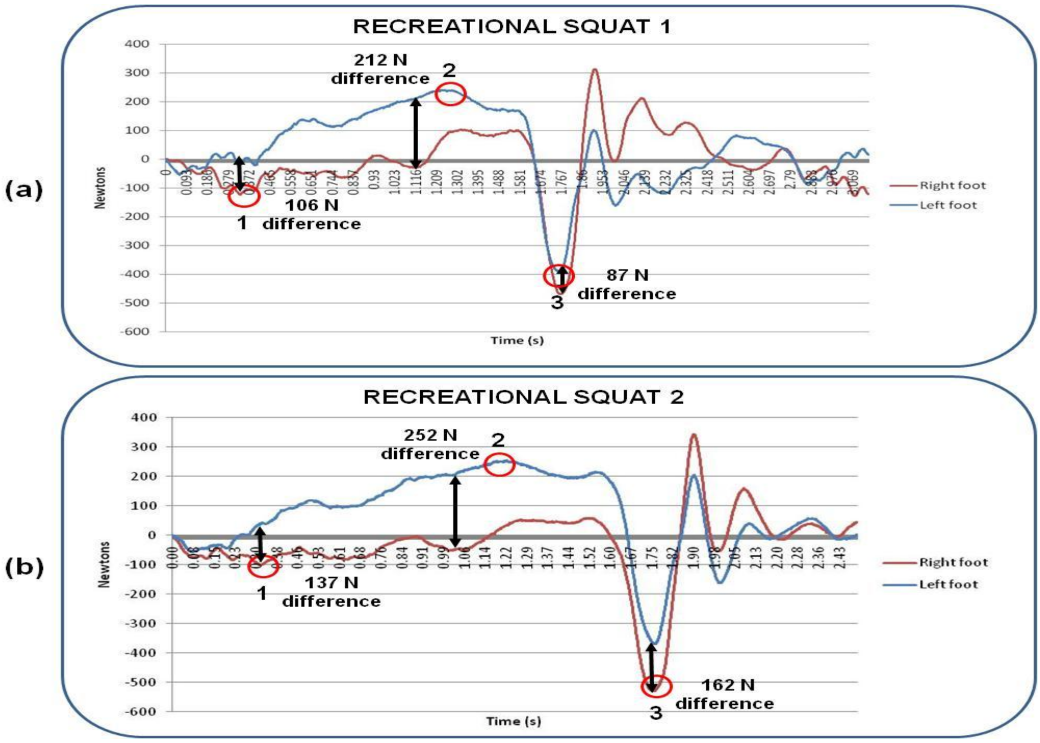


Figure 7.19 a and b Left and right foot force distribution during two recreational squats

Figure 7.20 a and b Left and right foot force distribution during two elite squats

It is clear that force generation is not evenly distributed in the recreational squat. The recreational subject leans to the left slightly and therefore exerts more force from the left hand side. This puts more pressure on the knee joint and could lead to injury. Maximum imbalance occurs between phases 1 and 2 for the first (a difference of 212 N between each foot) and second recreational squat (a difference of 252 N between each foot) (see Figure 7.19 (a) and (b)). This is when maximum work is done against gravity during the concentric phase and could inhibit the ability to generate force. In contrast, Figures 7.20 (a) and (b) indicate that force distribution is more balanced during the elite squat, whilst the three phases are more distinct. The results suggest that the use of two force platforms is essential for identifying unequal force generation, in preventing injury and improving technique.

To quantify the bilateral difference and resultant subject lean, the difference between the right and left foot was calculated for a recreational and elite squat. The results are plotted against the corresponding total net GRF for the recreational subject (Figure 7.21) and elite subject (Figure 7.22). The net GRF was used to distinguish which subject generated a higher peak force. The velocity data derived from the force platform were integrated to calculate the displacement which is plotted to identify the eccentric and concentric phases of the squat. Despite the reduced accuracy of the displacement data derived from the force platform for the recreational subject (see Figure 7.21), it is clear that the elite subject squats lower (0.6m) (Figure 7.22) and spends longer in the eccentric phase (1.6 s) than the recreational subject who only squats to a depth of 0.3 m in 1.07 s.

The elite subject generates a higher peak force (541 N) (Figure 7.22) than the recreational subject (316 N) (Figure 7.20), whilst the elite peak imbalance occurs near the beginning of the eccentric phase (0.92 s) (see Figure 7.22). The recreational subject reaches a peak imbalance at the start of the concentric phase (1.15 s), this is a crucial point in the execution of the squat as the subject is required to drive against gravity from zero velocity. Unequal distribution of force during this phase is likely to increase the risk of injury and inhibits force production, reducing peak force.

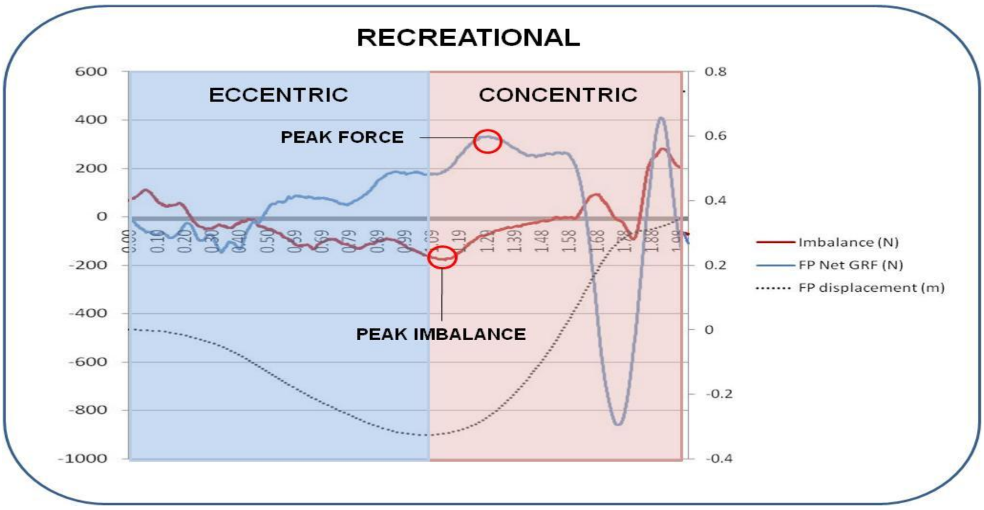


Figure 7.21 Identification of the peak force and peak imbalance using force platform analysis for a recreational squat

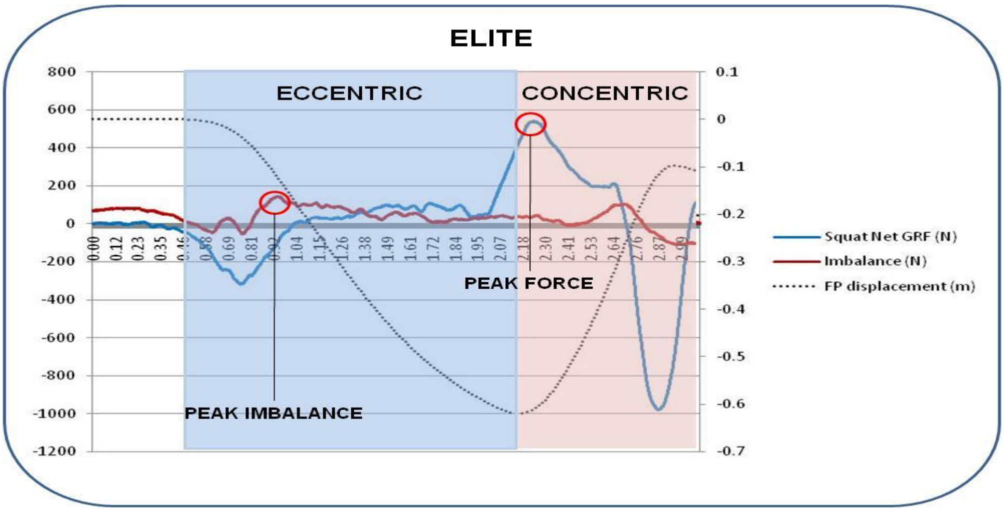


Figure 7.22 Identification of the peak force and peak imbalance using force platform analysis for an elite squat

The effect of joint loading and hip and knee torque forces during the squat is discussed by Fry et al (2003). Torque forces increase during the eccentric phase of the squat in which the subject descends. The maximum torque forces are experienced as the subject transfers from the eccentric to concentric phase, rising from the maximum knee bend. The ability to identify when maximum imbalance is occurring would enable coaches to prevent the likelihood of injury (Zhang et al 2004). Calculating the left to right peak imbalance in relation to the overall force generated as a percentage may provide an immediate form of performance feedback that could be implemented in a gym environment. Identifying the point at which this peak imbalance occurred is crucial in determining the impact of such imbalance (for example a high peak imbalance occurring during the eccentric phase as the bar is lowered would not impact performance as much as a peak imbalance occurring during the concentric phase as the bar is driven against gravity). The time at which the peak imbalance consistently occurs may indicate further differences between recreational and elite performance. Therefore distinction between elite and recreational performance would benefit from system functionality that identifies the peak imbalance between the left and right foot as a percentage of total force generated and the phase in which it occurred. For this functionality, a double force platform is essential. The remainder of this section documents the design generation of a double force platform design suited to a gym environment.

7.5.2 Ixthus 3-Axis Force Platform Design

This section documents the design of a double force platform system manufactured at Loughborough University. Rather than using existing products, the components of a force platform were decomposed to design a force platform system at a reduced cost (<£3000), reduced thickness (<65mm) and dimensions that accommodate two separate plates on a lifting platform (900 x 500 mm ± 10mm) to fit within the HiPac Training Centre at Loughborough University. Two types of transducers were supplied by Ixthus to measure both vertical and lateral GRF. The overall assembly of one force platform is illustrated in Figure 7.25. Each component is discussed in Table 7.4 whilst the design specification and cost comparison to an off the shelf Kistler force platform is located in Appendix D.

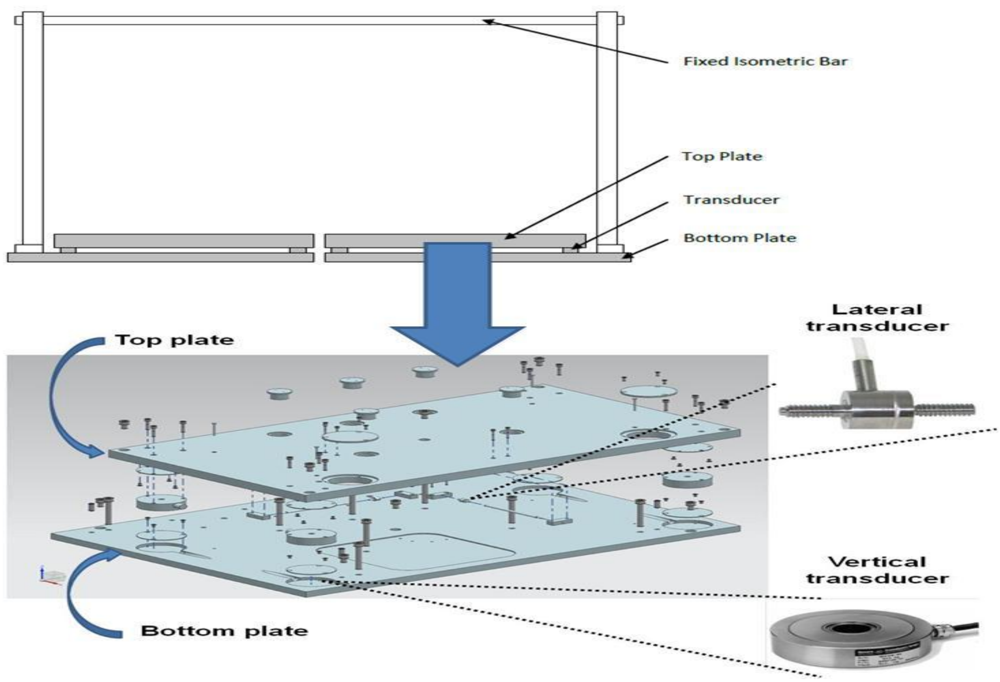


Figure 7.23 Design generation of a double plate force platform suitable for the gym environment.

The plates were designed to accommodate a weight lifting platform, ensuring that they were still surrounded by shock absorbing material. An isometric bar was also included to allow for a wider range of exercises to be executed and monitored using the force platform. The elite based system is designed to monitor both body and bar movement to ensure that complex exercises are accurately monitored. The results from this Chapter indicate that bar and trajectory rotation generated during complex exercises can only be monitored using a WIMU that is securely attached to the bar. The redesigned bar attachment successfully prevented device rotation and wireless transmission was not affected. Determining the efficiency of the lift requires GRF data as well bar kinematic data, for which a WIMU and force platform is required.

Component	Detail
Vertical transducers	• Torsion load cell which is located between top and bottom plates in each corner and measures purely the vertical (Z) force (83) • The load cell was inserted upside-down so that the transducer could be secured through the top plate • Load cell was not fixed to the bottom plate, allowing the top plate small lateral movements through which the exerted lateral force could be captured.
Lateral transducers	• The second type of transducer was a tension and compression load cell model 8417 (84). • Two were positioned perpendicular to each other to measure the lateral force components (X & Y) exerted on the plate • The transducer has a deflection limit of 60µm along its axis, but was sensitive to any shear force applied.
Bottom plate	• Dimensions of 896x646mm = wider than the top plate to provide space for an isometric bar attachment. • Seven levelling screws provided a means to level the plate. • Series of holes allowed for the plate to be securely clamped down to a concrete floor. • The space for 4 cylindrical transducer spaces to allow for the vertical load cell transducers to 'float'. • Stainless steel disc inserted above and below each vertical load cell to prevent issues with material interaction between the stainless steel vertical load cell and aluminium plates. • Central recess to accommodate a lateral force measurement system which required two pairs of holes for securing two transducer blocks to the bottom plate.
Top plate	• Dimensions of 896x500mm = available area over which force can be exerted. • Ground bolts and levelling screws to the outer edge of the bottom plate left uncovered by the top plate to allow for calibration. • Central and inner bolts and screws have had access provided to them through the top plate with small (Ø=30mm) threaded access holes, and two larger (Ø=70mm) access holes.

Table 7.7 List of main components required to develop a double plate force platform.

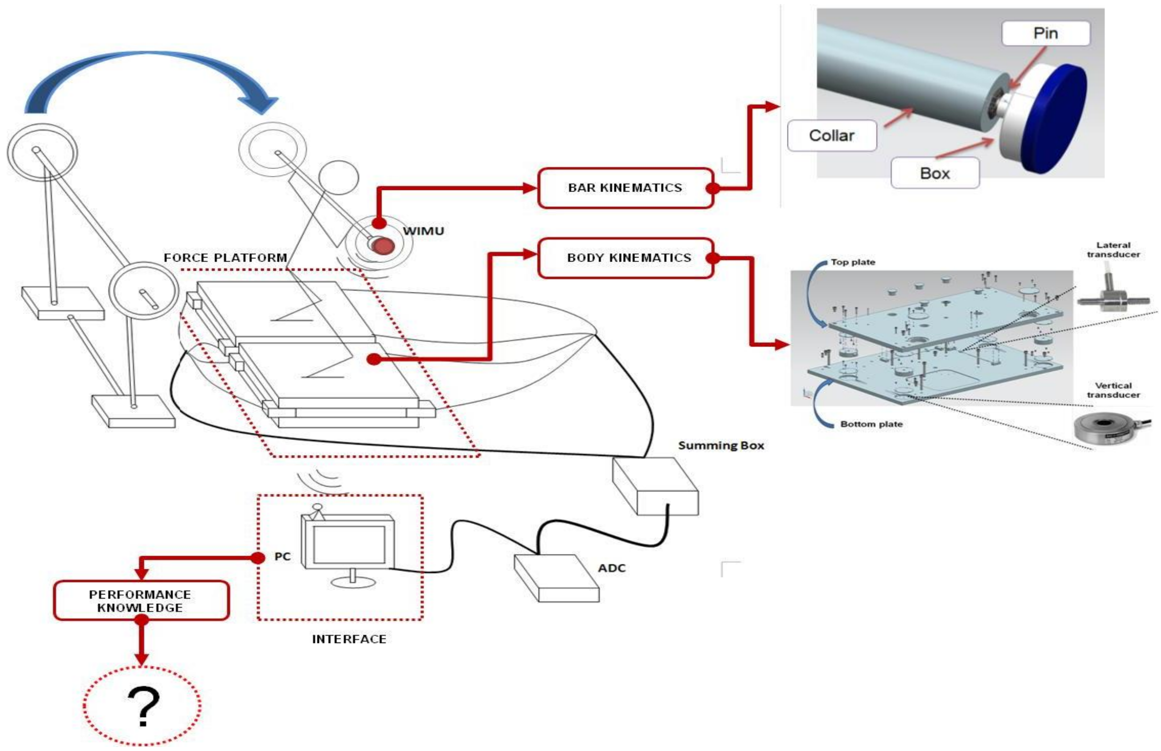


Figure 7.24 Design of a combined double plate force platform and WIMU system to monitor elite performance in a gym environment.

7.6 Brief Chapter summary

TARGET OBJECTIVE:

Identify the most appropriate forms of technology to develop a combined system that supports the analysis of elite performance in the resistance training domain.

TARGET RESEARCH QUESTIONS:

How can the effects of rotation be minimised to improve the analysis of complex exercises?

Three forms of rotation exist, rotation that is irrespective of the bar and is attributed to the bar attachment design, bar rotation and trajectory rotation. Case study 1 indicated that linear exercises can be greatly affected when only one type of rotation is present. Therefore it can be assumed that this error is amplified further once bar and trajectory rotation is introduced. Both bar and trajectory rotation require more sophisticated technology. A WIMU is required for monitoring at the elite level as bar and trajectory rotation are fundamental to complex exercise execution.

Which monitoring methods should be combined to increase performance knowledge gained and system validity of an elite based system?

The results from Case study 2 indicated that the integration of a gyroscope with a tri-axial accelerometer to form a WIMU increased both WIMU and video (from 0.175 to 0.857^{**}) and WIMU and force platform (0.034 to 0.901^{*}) correlation. To calculate lifting efficnecy for a complex exercise, the power generated by the lower body and resultant power transferred to the bar must be calculated. The difference between the bar and body peak variables can also be used to distinguish between elite and recreational performance as a measure of efficiency. For this analysis both WIMU and force platfrom technology is essential. Whether a subject leans significantly to one side during a lift can be identified in the WIMU acceleration profile using the axis positioned along the bar. Determining whether the lean originates from unequal force distribution from the right and left foot or is attributed to poor alignment of the upper body can only be determined using a combined bar mounted WIMU and double plate force platform. The results from Case study 3 indicated that differences in squat performance between an elite and recreational subject could be identified by considering the bilateral difference throughout the execution of the lift using two force platforms. The ability to identify peak imbalance and time to peak imbalance throughout any lift could aid the identification of weakness or prevent injury. Although the processing complexity is increased, the performance knowledge gained using a combined WIMU and double plate force platform system is much higher than with a simple tri-axial accelerometer. The increased knowledge is identfied in Figure 7.27. An overview of the knowledge acquired as result of this Chapter is presented in Figure 7.28.

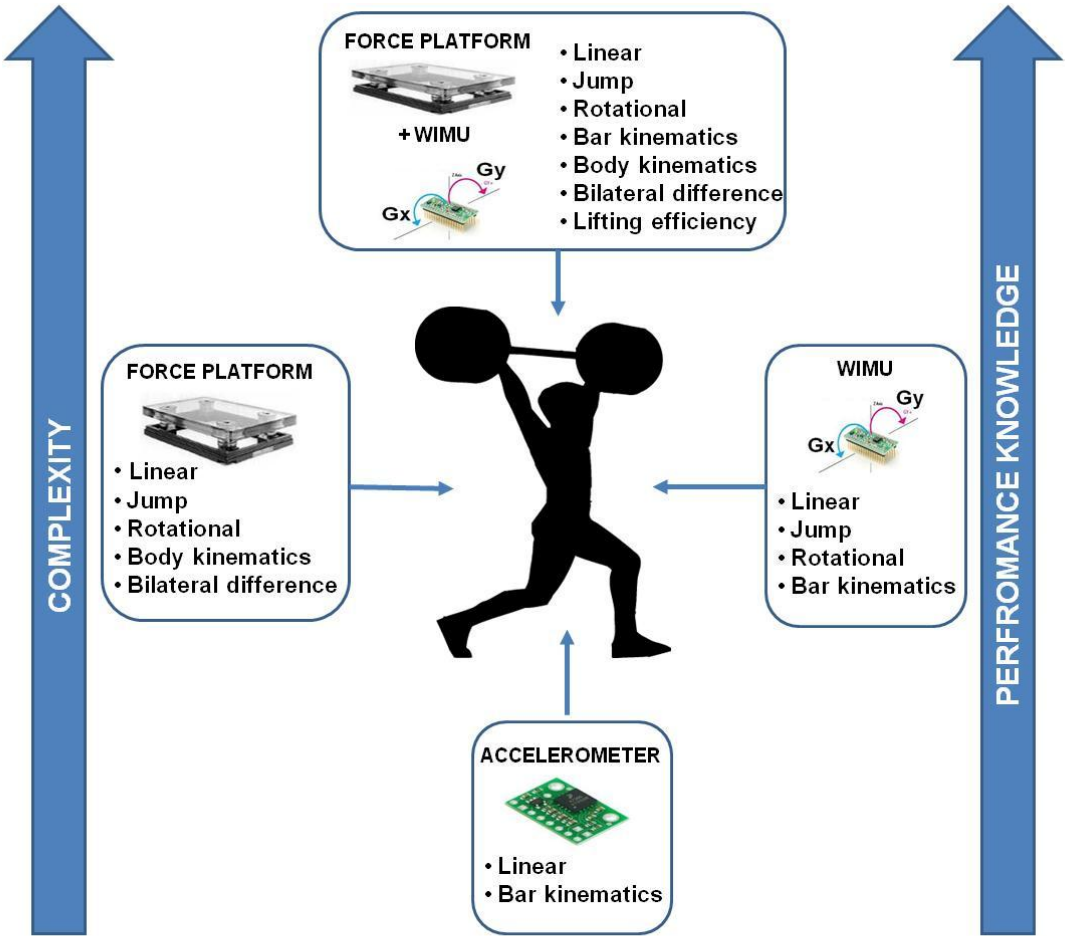


Figure 7.25 Summary of the increase in technology sophistication required as exercise complexity and the desire for performance knowledge increases.

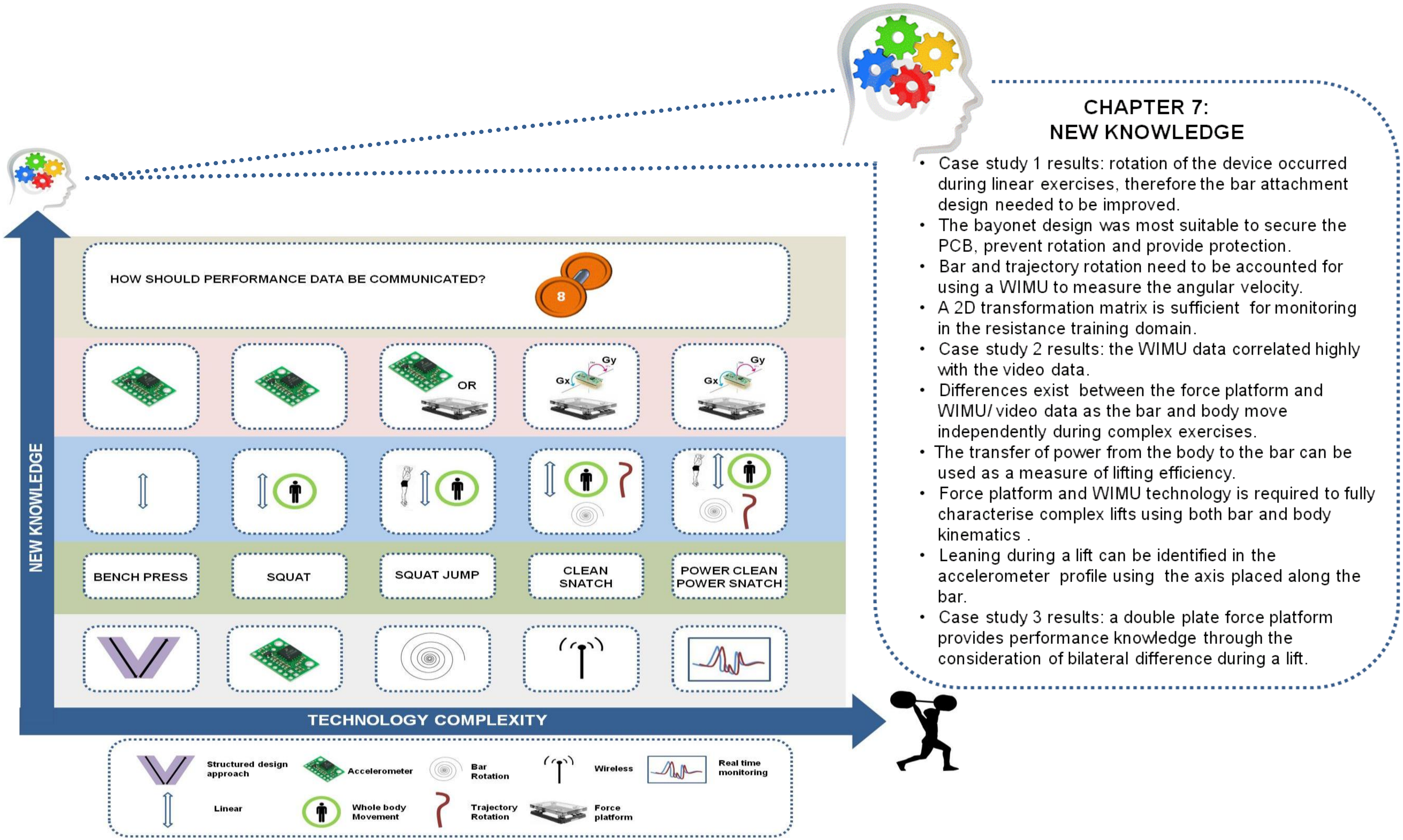
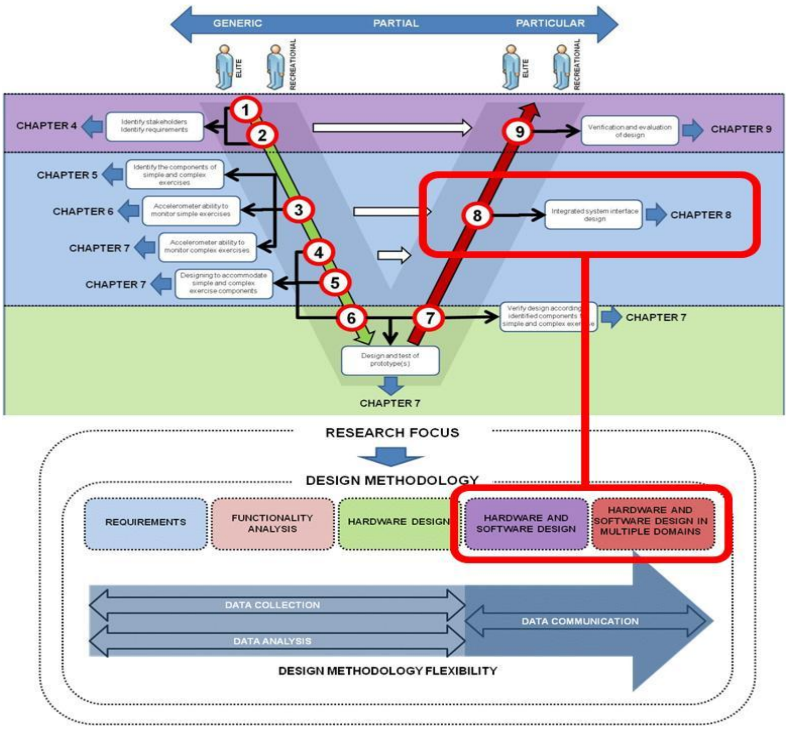


Figure 7.26 The identification of new knowledge acquired and core question findings; Both WIMU and force platform technology is required to monitor the bar and body movement experienced during complex exercises.



Chapter 8

8.0 Software development for an elite performance monitoring system

TARGET OBJECTIVE:

To apply the proposed combined methodology to design supporting software for an elite based performance monitoring system and determine the flexibility of the proposed combined methodology.

TARGET RESEARCH QUESTIONS:

- *Can the combined methodology be applied to the software domain?*
- *How does the combined methodology promote user-centred design?*
- *Is the design methodology flexible?*

8.1 Introduction

The focus of this research has been to investigate the advantages of adapting a structured process to design a system suitable for elite performance monitoring in the resistance training domain. As specified in Chapter 1, in order to gain performance understanding in the sports domain, three aspects must be considered, the collection, analysis and communication of data. The previous chapters have documented the application of the proposed design methodology to investigate the design of suitable hardware and analysis methods for elite monitoring. The aim of this Chapter is to investigate the application of the proposed methodology to target how the data are communicated to the user through software design. One of the main targets of the methodology was to ensure it was flexible, therefore, whether the same methodology can be applied to another sporting domain. An evaluation of this flexibility is provided by detailing the design of a GUI for monitoring elite swimming performance.

8.2 Application of the combined methodology to support software design within the resistance training domain

The combined monitoring system developed in Chapter 8 was designed following thorough decomposition of the subsystems identified within the domain (linear, dynamic jump and rotational movement). The testing results were then integrated to form a combined system. The application of the proposed methodology to support software design requires less testing and more focus upon understanding the type of data flow within the current domain and how to accommodate the new data flow. A review of the methodology first proposed in Chapter 2 is presented in Table 8.1. The methodology applied to software design is illustrated in Figure 8.1.

The previous chapters have focused on investigating the capability set of the technology and integrating user needs to aid the development of system functionality and hardware product design specification. However, as discussed in Chapter 2, how the user interacts with the product is a fundamental aspect of successful design. The systems analysis and domain classification provided an overview of the proposed and current system to identify the data flow. This gave some indication of the structures that need to be in place to accommodate such a system-whether they are physically or logically based. Therefore the aims of the remaining design process stages are to integrate further the user needs specific to the interface design. At the user requirements elicitation stage, the questionnaire was designed to gain functionality and visualisation based feedback, therefore consideration of the user interface must still begin in the initial stages when gathering user input. The suggestion is that when a product requires both software and hardware design the final stages allow the developer to investigate fully the user interaction from a software perspective. Similarly, if a product does not require any software development stages 1 to 5 can all be conducted in the proposed order to provide a structured design process for the functionality and hardware.

The full model has been reapplied to structure the software design process. The definition of objectives was addressed in earlier Chapters, however, re-iteration of the design objectives in relation to the software design alone is required. The *user requirements* specific to software design are also derived from the testing conducted in Chapter 4. *Feasibility testing* of the hardware has been conducted and the capability of the system is understood, therefore, the software can be designed according to the known capability of the product rather than through assumption. The remaining steps are investigated in the remainder of the Chapter.

STEP	AIM	MODEL/MODELLING TECHNIQUE
1	**Define objectives**	SSADM
2	**Define user requirements**	"vee" process model Spiral process model
3	**Feasibility testing**	SSADM "vee" process model
4	**Systems analysis**	CIMOSA SSADM "vee" process model
5	**Domain classification**	CIMOSA SSADM "vee" process model
6	**Business process analysis**	CIMOSA SSADM "vee" process model
7	**Consolidation of the subsystems and design generation**	"vee" process model
8	**HMI task analysis**	HMI storyboarding "vee" process model SSADM
9	**Consolidation of HMI tasks**	HMI storyboarding "vee" process model

Table 8.1 Proposed design methodology and corresponding model/modelling techniques.

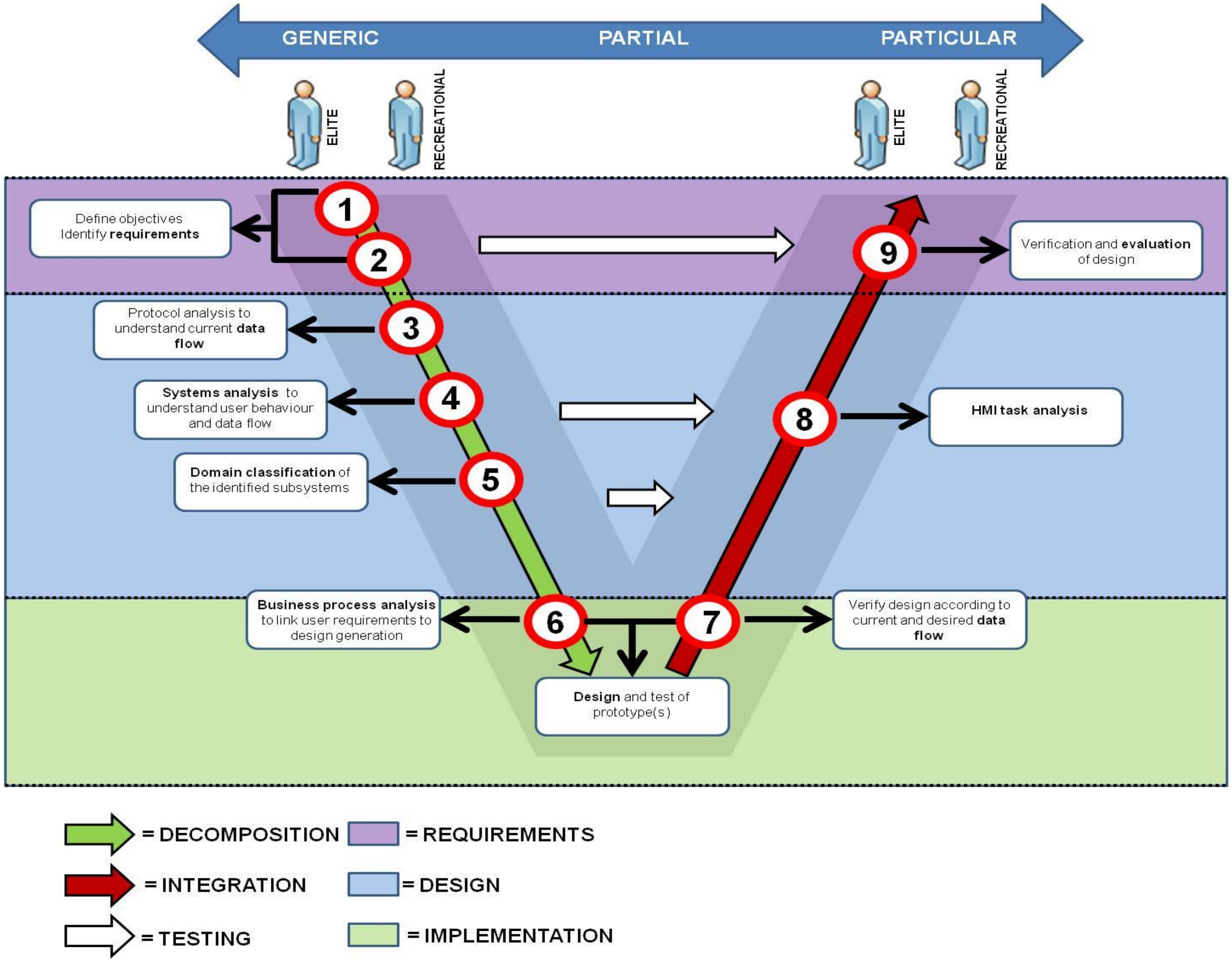


Figure 8.1 Proposed combined methodology applied to the software domain.

8.2.1 Define objective(s)

The objective of the methodology application is to:

"design supporting software for an elite based performance monitoring system in the resistance training domain"

The testing required to understand the capability of the system has been investigated in Chapters 5-7. Testing conducted through protocol analysis also identified further software related user requirements, further supporting the use of the re-iterative nature of the methodology. An overview of the user requirements is presented in the next section.

8.2.2 User requirements

The definition of user requirements using both conversational and observational techniques was discussed in Chapter 4. The techniques were used to identify the hardware and software requirements. Therefore, as well as requiring real time analysis, the user needs specifically related to communication of the data are identified in Figure 8.2. The initial software user requirements identified the need to provide a choice of both graphical and numeric display. The monitoring of training inputs refers to the need to provide *rest to work time* feedback, a *record of sets and reps* and resultant *training zone identification* (endurance, hypertrophy, strength or power). Feedback is mostly desired in the time between sets but a record of data is required to allow the user to compare performance and refer to *past data post session.*

The GUI requirements were also derived as a result of the hardware testing and product capability (see Chapters 5-7). The limitation of the integration error in the data identified the need to select the start and end of individual reps before analysis is undertaken. Therefore the software must provide a method for selecting each rep or calibrating each exercise to allow a correlation algorithm to be used (Oppenheim and Schafer 2010). The ability to determine *readiness to perform* for elite and recreational calibration and the need for both *bi-lateral force platform* and *WIMU* feedback also heavily influences the software design. Therefore, to decompose further the user requirements, the steps identified in the combined methodology were followed. Each step is documented in this Chapter.

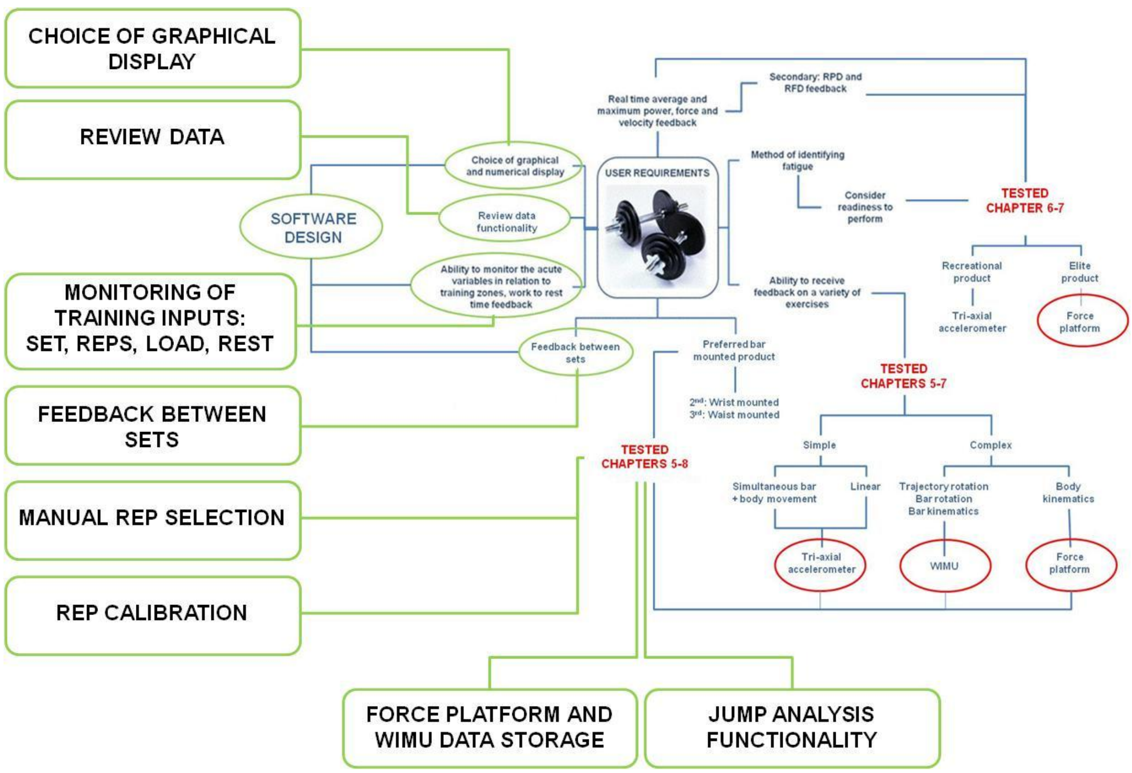


Figure 8.2 Using the original user requirements and testing requirements to derive software requirements.

8.2.3 Systems Analysis

Collecting user requirements throughout the design process only forms one element to successful user-centred design. In order to understand fully the system requirements from the developer's perspective, there needs to be an understanding of the current system and the proposed system so that comparisons can be made in terms of improved data flow and interaction. As stated previously, this is generally a "fact-finding" stage which focuses on producing models and diagrams of the current system. Data flow modelling is utilised to form *context diagrams* and *data flow diagrams* which establish the internal and external entities in the weightlifting domain and the flow of data between them. Current performance analysis in the weight lifting domain has to be considered from an elite and recreational point of view. A context diagram for both the current elite and recreational analysis system is illustrated in Figures 8.3 and 8.4 respectively. The context is investigated further using data flow modelling to identify the current data flow between the internal and external entities from the elite and recreational view, illustrated in Figures 8.5 and 8.6.

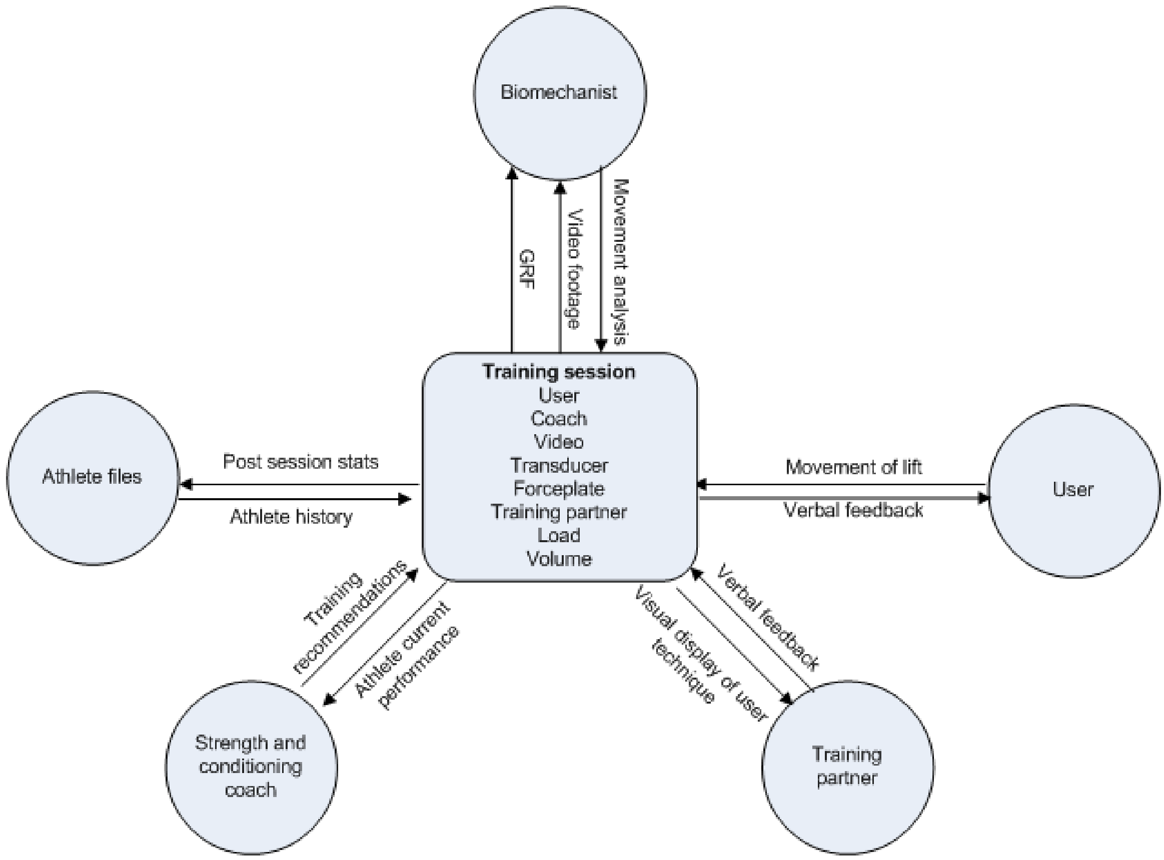


Figure 8.3 Elite weightlifting environment context diagram

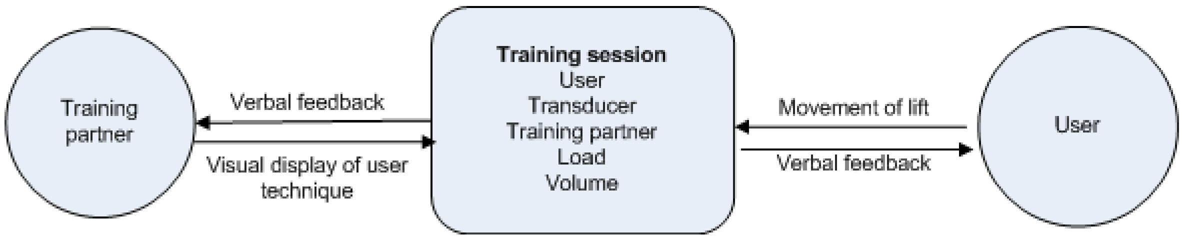


Figure 8.4 Recreational weightlifting environment context diagram

Both the elite and recreational users have very different data flow models (see Figures 8.5 and 8.6). The elite require more feedback from numerous external entities to gain a good understanding of performance (e.g biomechanist, nutrionist, sport scientist and coach input is often required). The current effectiveness of such communication is limited due to the reliance on verbal communication between the sports professionals. In order for the training programme to be optimised, the sports professionals need to be able to view all data to prevent overtraining or regression (ACSM 2002). The recreational data flow model is less complex, simply requiring input from a training partner and manual logging of the load and volume lifted. The results from Chapter 4 indicated that although users were aware of other monitoring devices such as heart rate monitors, they were not commonly used to gauge performance during weightlifting. Accommodating the proposed system data flow is reliant upon providing an appropriate software structure that collects, analyses and communicates athlete data. The proposed data flow model is illustrated in Figure 8.7. To determine how to accomodate the data flow model, the general themes generated from the user requirements and systems analysis were categorised to form a basic structure from a software perspective. This was conducted through *domain classification* (see Table 8.2).

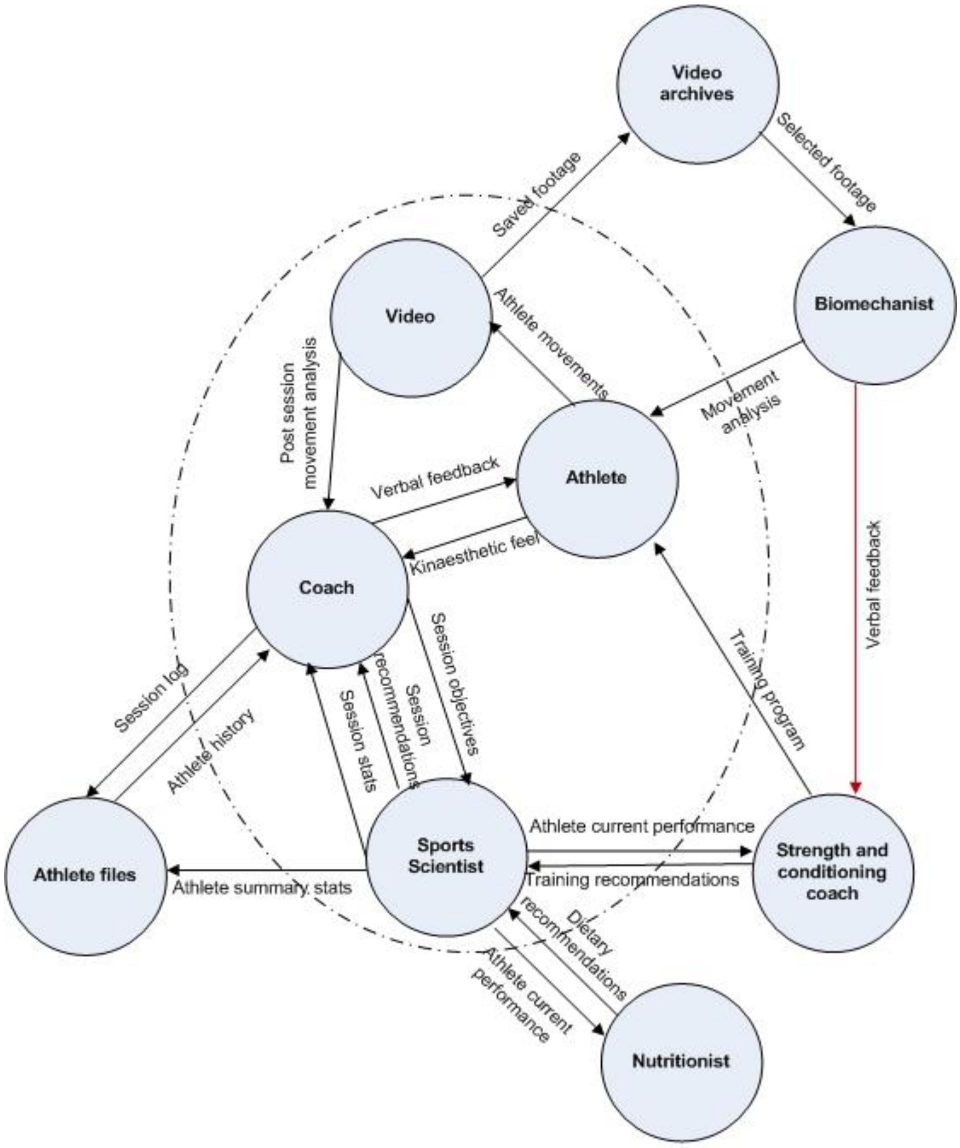


Figure 8.5 Data flow modelling in the elite environment

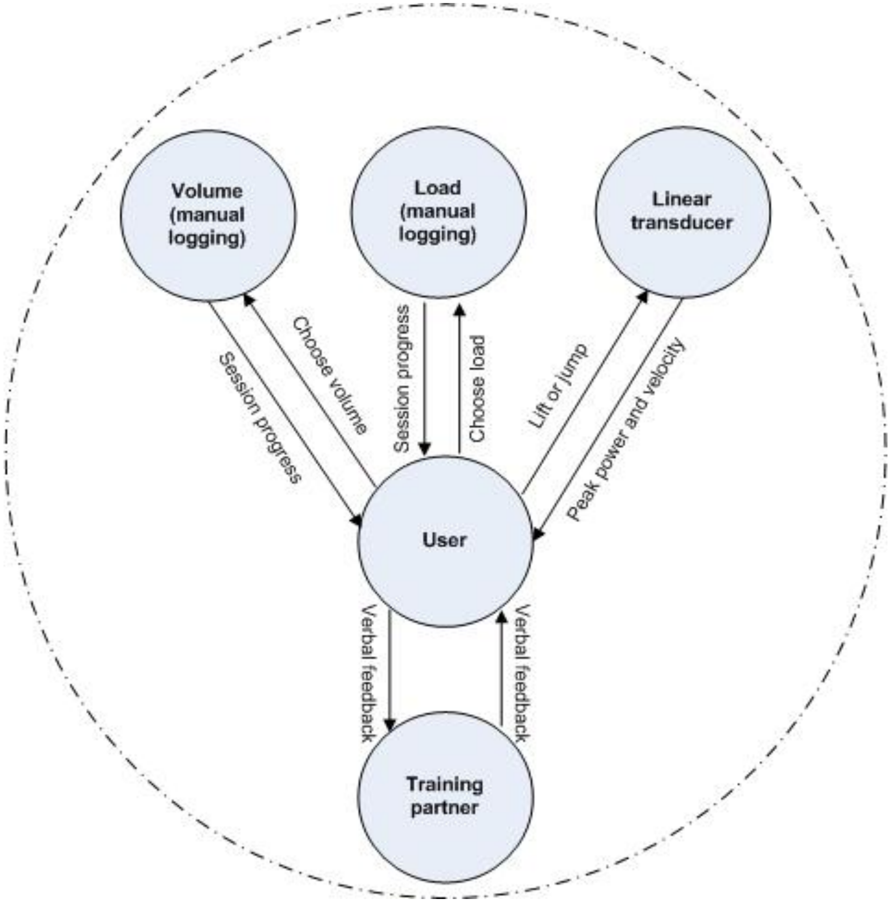


Figure 8.7 Data flow modelling in the recreational environment

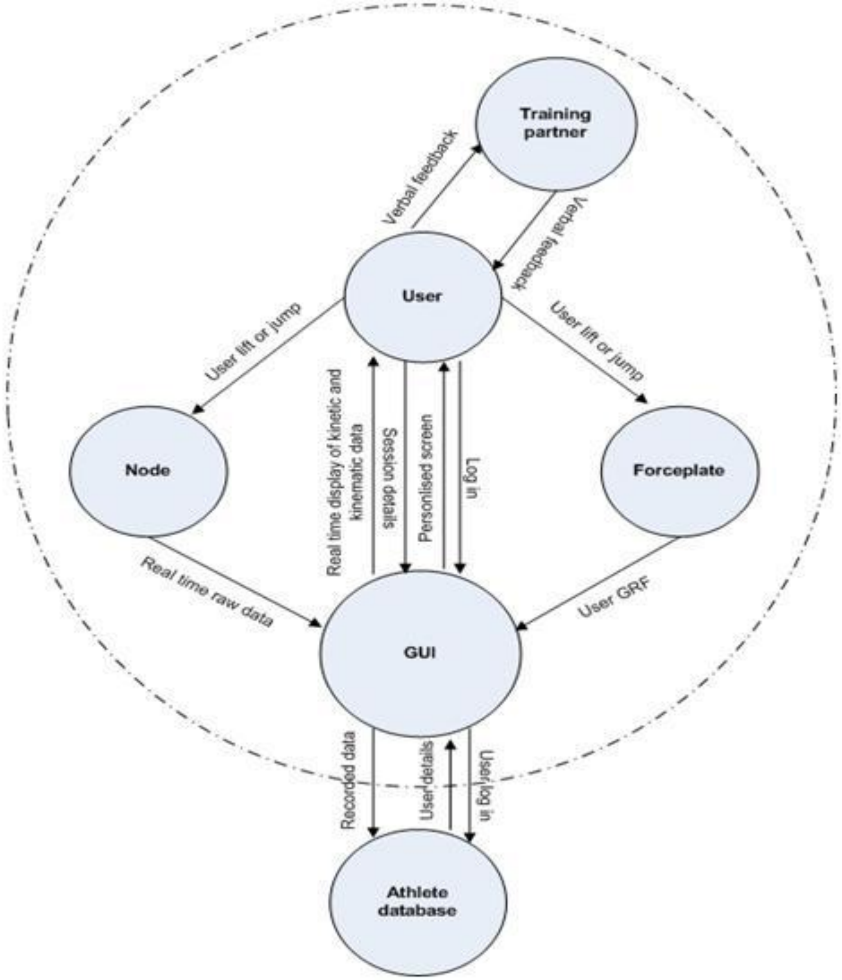


Figure 8.6 Proposed data flow model for the weightlifting domain

8.2.4 Domain Classification

Using both the user requirements and systems analysis data it was previously concluded that the system would need to provide real time feedback both during and after the set. Following the feasibility testing it was also concluded that collection of the desired parameters for both elite and recreational users would require forceplate and WIMU data. An overview of the domain classification and domain processes within each domain is presented in Table 8.2. The domain processes relate to the likely interaction with the system according to the domains outlined in Table 8.2. The design methodology followed throughout this project aims to avoid the common mistakes experienced when software development is an afterthought to the hardware design or vice versa.

Enterprise Domain	Name	Domain Process	Explanation
DM1	Real time feedback from node	**BP1.1**	Login access validation
		BP1.2	Select training analysis
			Select jump or lift
		BP1.3	Identify that node is activated
		BP1.4	Input session variable s(load, sets, reps)
		BP1.5	Begin collection of raw data
		BP1.6	Filter data for meaningful kinematic variables
		BP1.7	Choice of delivery – graphical or tabular
		BP1.8	Save data to database
DM2	Real time feedback from forceplate	**BP2.1**	Login access validation
		BP2.2	Select jump or lift
		BP2.3	Begin collection of data
		BP2.4	Save data to database
DM3	Data storage	**BP3.1**	Login access validation
		BP3.2	Save data according to date and username
		BP3.3	Update when user profile is edited
DM4	Post analysis	**BP4.1**	Login access validation
		BP4.2	Select date(s) to view or compare
		BP4.3	Retrieve data from database according to username and date (s) selected
		BP4.4	Choice of delivery – graphical or tabular
		BP4.5	Export session configuration to pdf
DM5	Configuration	**BP5.1**	Add user
		BP5.2	Edit user
		BP5.3	Edit exercise directory
		BP5.4	Zero forceplate
		BP5.5	Check node battery life

Table 8.2 List of domain processes existing within each sub domain

8.2.5 Business Process Analysis

The aims of the remaining design process stages are to integrate further the user needs specific to the interface design. Functional decomposition of the business processes is demonstrated in Figure 8.8 the resultant Level 2 and Data Flow Diagrams (DFDs) are illustrated in Figures 8.9 and Figure 8.10. The method of functional decomposition allows the developer to view the overall system in a structured manner. The inputs needed to plan a session and how these inputs can be obtained by each individual user is presented in Figure 8.9. The *Date*, *Time* and *Username* will be crucial in ordering input values and storing data specific to each user. Consideration of weaknesses is reliant upon the ability to collect the data and retrieve it for comparison at a later date. The training goals will be dependent on the acute variables associated with a weight training session. In order to show progression during a training programme, load, sets, reps, rest time and exercise type, all provide a tool for manipulating the programme so it is specific to the user and their goals. Therefore, the system must allow for acute variable input.

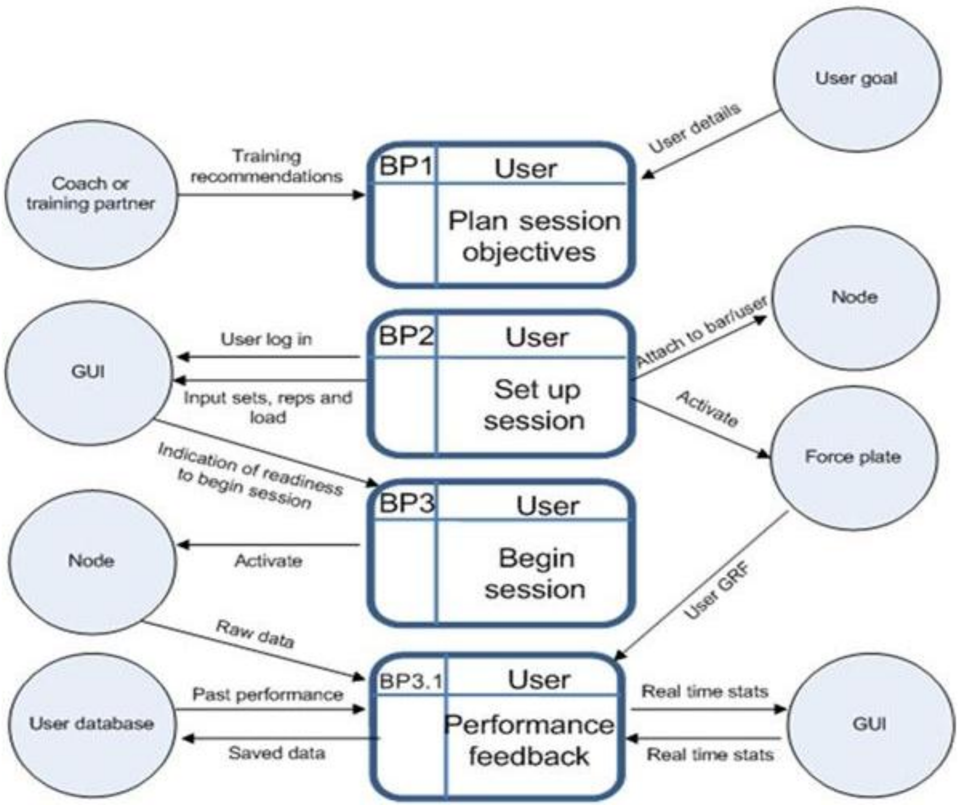


Figure 8.8 **Top level business process analysis within performance feedback domain.**

Functional decomposition of setting up a session is presented in Figure 8.10. Three central internal entities that require interaction in order to set up the session are identified. The Graphical User Interface (GUI) is a major component of this process, the nature a GUI access will influence the subsequent data that can be viewed, how this is done is not considered at this level. Both session objectives and acute variables are required to ensure the system is ready to collect the data the user in interested in. Setting up the session is reliant upon defining the session objectives, whilst the ease of setting up will have a great impact on the system's success. Being able to identify common session objectives or allowing the user to plan their session based on the objectives and input this to the system will have a great effect upon the resultant set up required.

Functional decomposition of beginning a session is presented in Figure 8.11. This is an ideal user interaction scenario in which data collection simply relies upon a "start" button, however, this level of decomposition does not detail how this will be achieved. The output values are identified but the processing of the data is not. How the user receives feedback upon their performance is decomposed further using a Level 3 DFD illustrated in Figure 8.12. This level highlights the need for differing statistical views, the storage of summary statistics, a comparative tool and a user database. Overall this method is not conclusive, it does not define the exact protocol of use but outlines software structure required to allow such processes to occur.

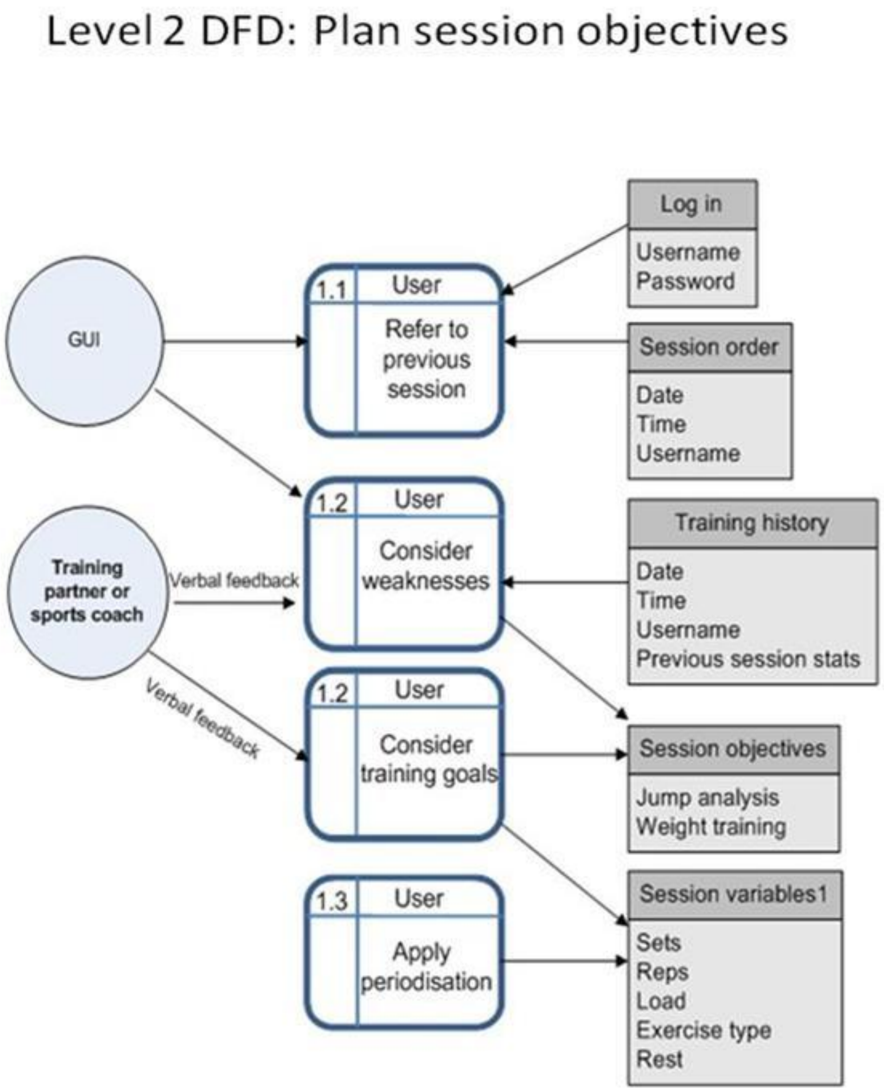


Figure 8.10 Level 2 decomposition of planning session objectives

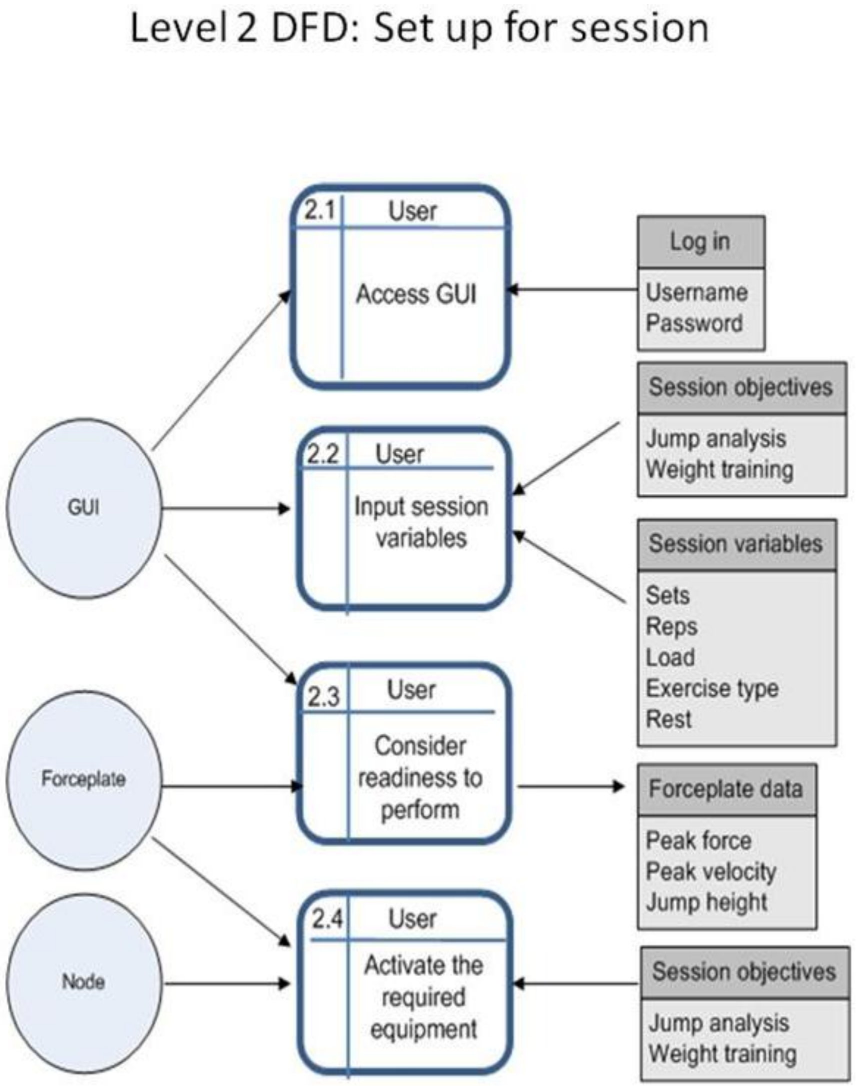


Figure 8.9 Level 2 decomposition of setting up session

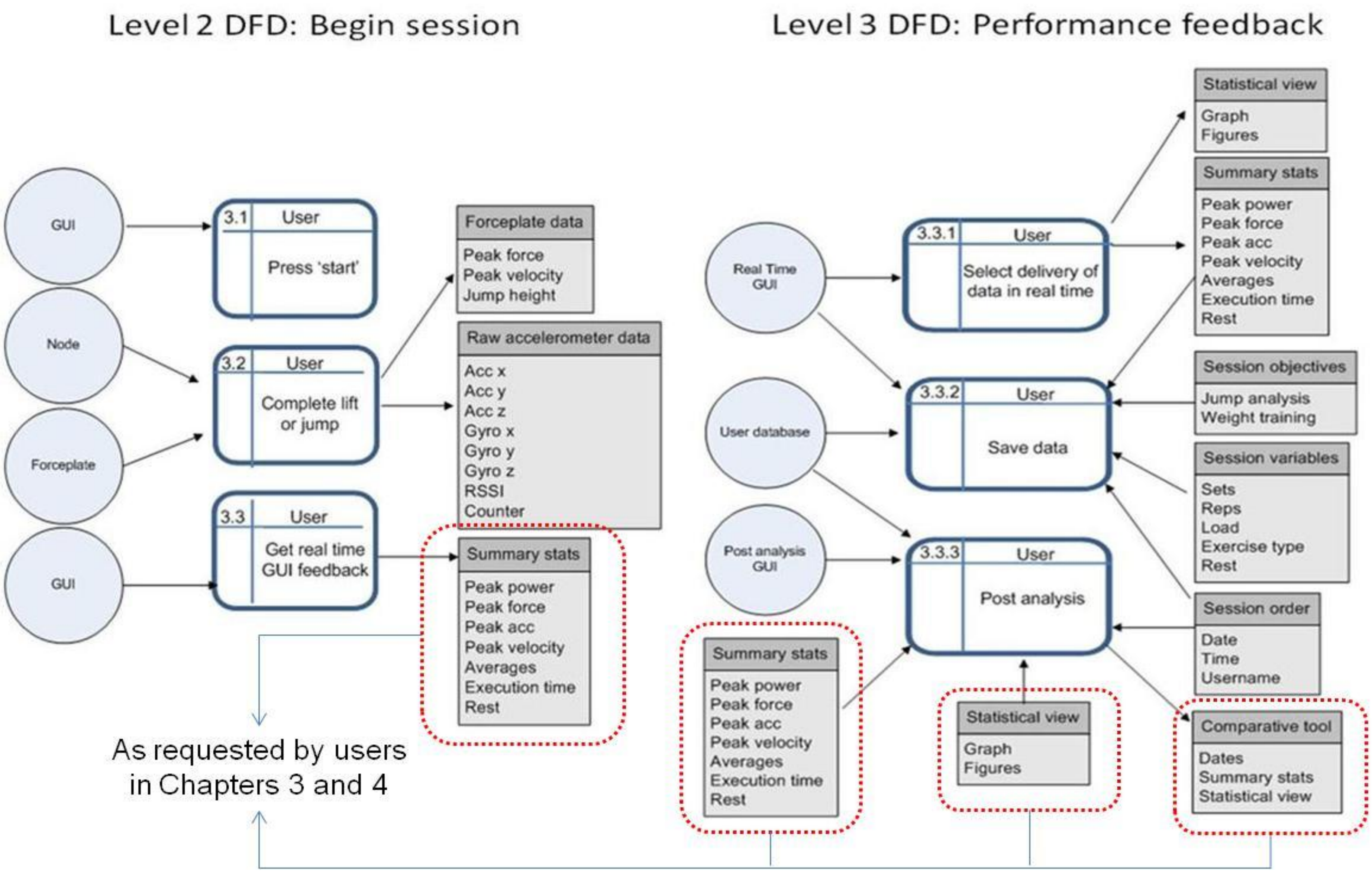


Figure 8.11 Level 2 decomposition of planning session objectives

Figure 8.12 Level 2 decomposition of setting up session

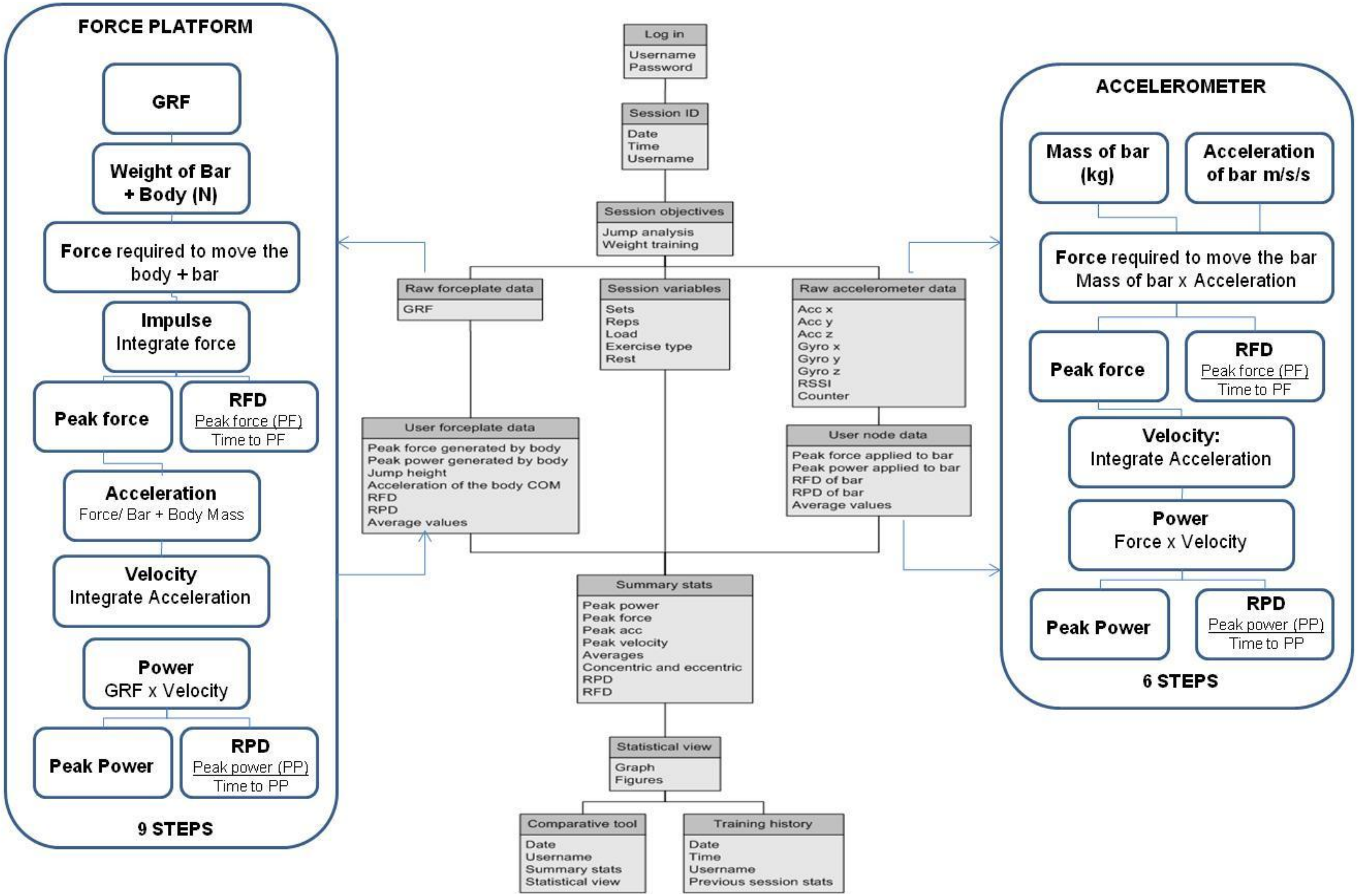


Figure 8.13 Overview of the data required to accommodate proposed system data flow

The data required to develop a suitable system are identified in Figure 8.13. The skeleton of software was developed using the design process methodology to determine the data flow within the current and proposed system environment. Using this structure as a basis for the software development, another form of analysis is used to understand how different user types would interact with the system.

8.2.6 HMI task analysis

In order to understand potential user interaction with a performance monitoring system within a gym environment, the web based questionnaire documented in Chapter 4 was analysed to investigate aspects of a Human-Machine Interface. The aim of the user interaction questionnaire section was to derive *preferred order of tasks* that users followed and identify whether user *interaction* decreased as the *number of HMI functions* increased.

The questionnaire required users to select the order and number of HMI functions to fulfil a given task. Three main tasks were identified using the results from the system decomposition through systems analysis and business process analysis (see Sections 8.2.3- 8.2.5). A list of possible options to complete the task was presented in a random order to the user so as not to influence the order of the tasks selected. An example of the questionnaire task analysis section is presented in Figure 8.14. The three tasks presented to the user were as follows:

1. Create a new profile
2. Start a new session
3. Review data

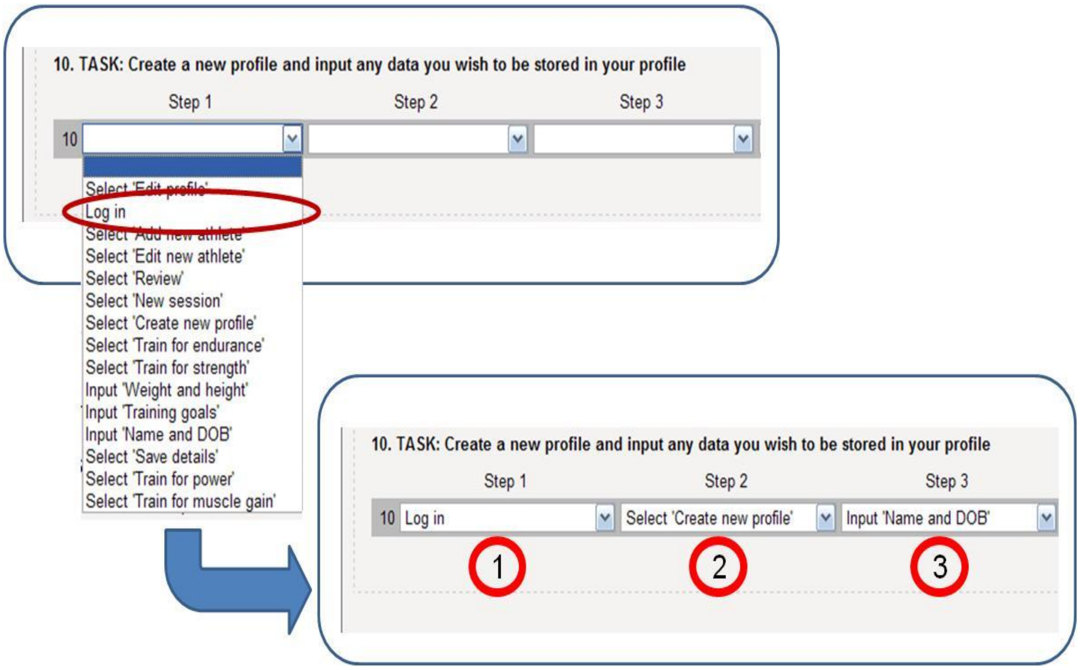


Figure 8.14 Example of the HMI questionnaire designed to investigate user interaction

8.2.6.1 HMI task analysis results

The results from the questionnaire are presented in Figures 8.15-8.17. The pie charts represent the spread of data regarding the function selected at each step, the most common step selected at that stage is identified on each step. The response rate is documented beneath the HMI steps. A summary of the task analysis data is presented in Table 8.4. The percentage response rate for each selected function is displayed in Figure 8.18. All three tasks resulted in a response rate between 80-100% to the third HMI step, furthermore, there is a significant decrease in response rate after the fifth HMI step. Therefore, the supporting software should focus upon ensuring that the number of steps required to perform a task should not exceed 5 steps. This would further improve the usability of the system (Ledoux 2005).

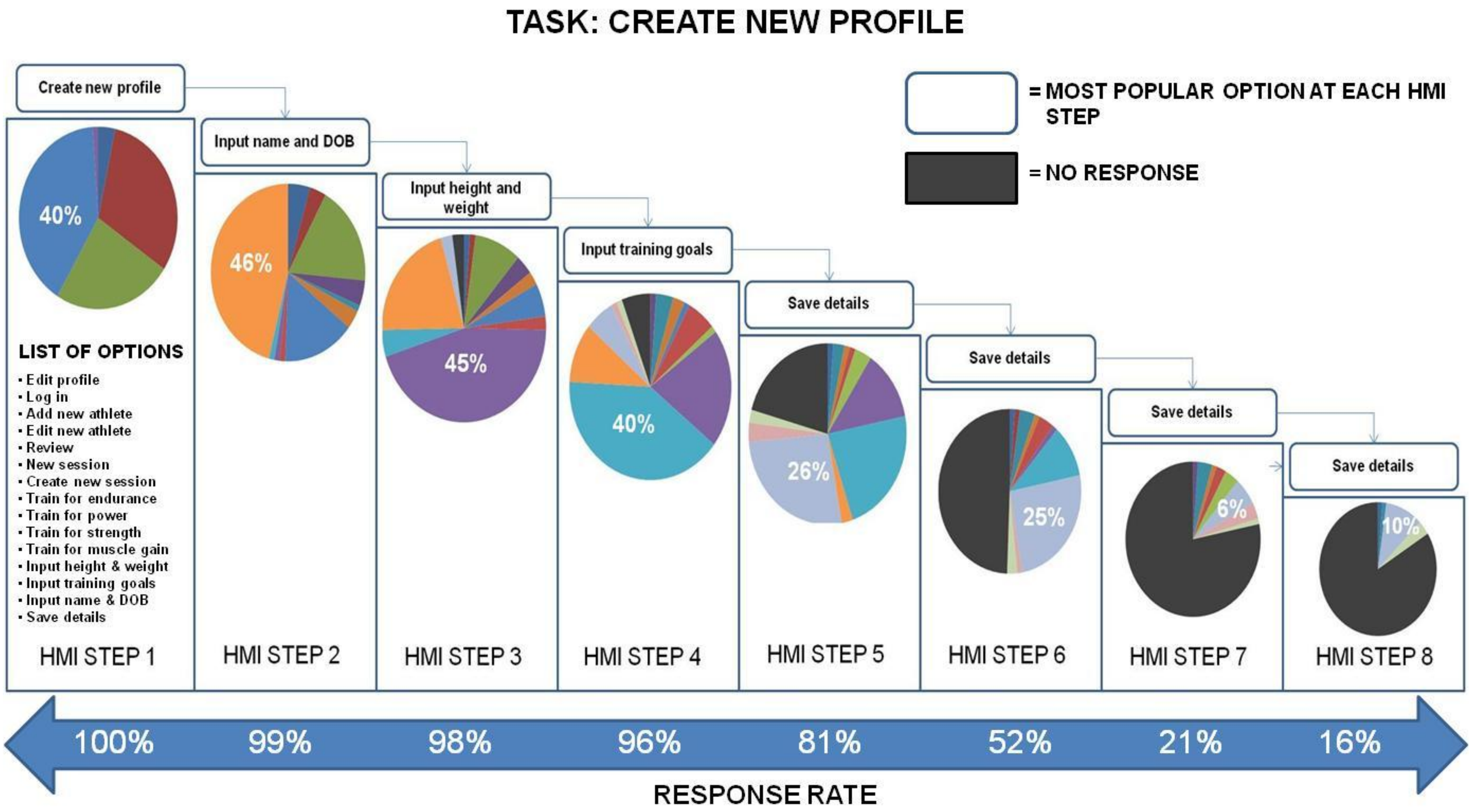


Figure 8.15 HMI user task analysis questionnaire results indicating the most preferred user interaction path for creating a new profile.

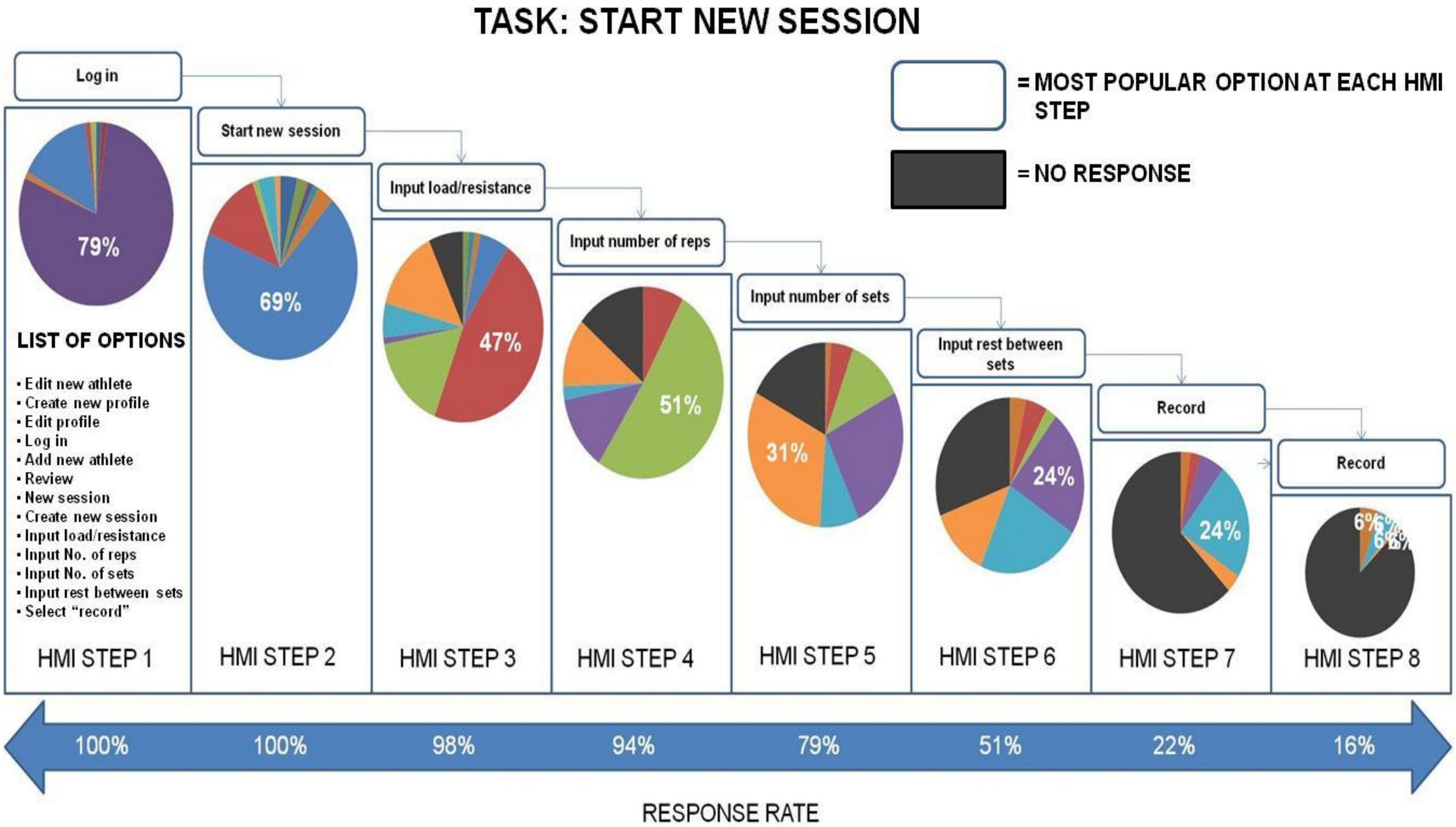


Figure 8.16 HMI user task analysis questionnaire results indicating the most preferred user interaction path for starting a new session

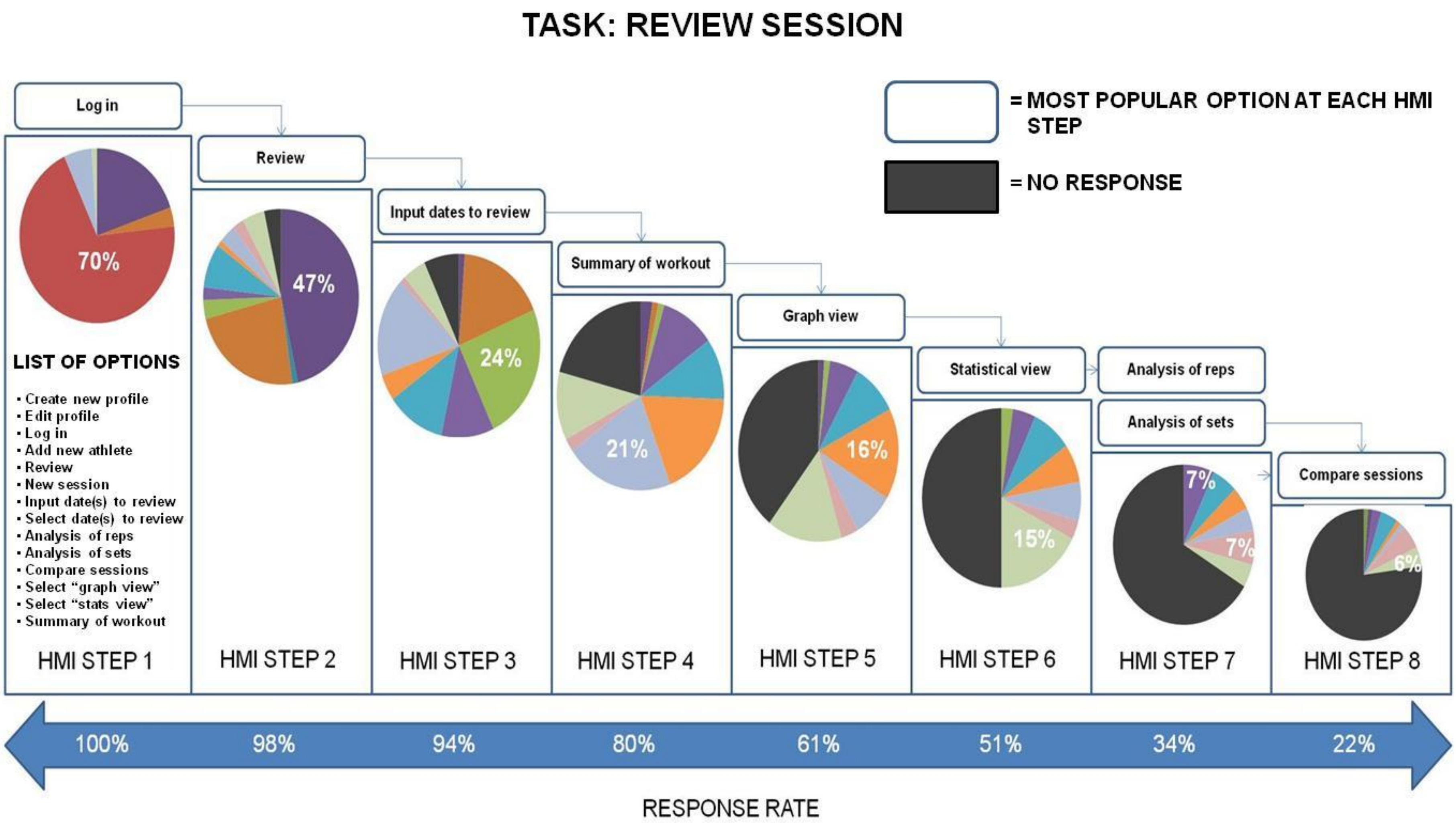


Figure 8.17 HMI user task analysis questionnaire results indicating the most preferred user interaction path for reviewing data.

	TASKS			
	Step	**Create new profile**	**Start new session**	**Review session**
Preferred step order	1	Create new profile	Log in	Log in
	2	Input name and DOB	Start new session	Review
	3	Input height and weight	Input load/resistance	Input dates to review
	4	Input training goals	Input number of reps	Summary of workout
	5	Save details	Input number of sets	Graph view
	6	Save details	Input rest between sets	Statistical view
	7	Save details	Record	Analysis of reps/sets
	8	Save details	Record	Compare sessions

Table 8.3 Summary of HMI task analysis questionnaire results identifying the most preferred order of steps to complete each task.

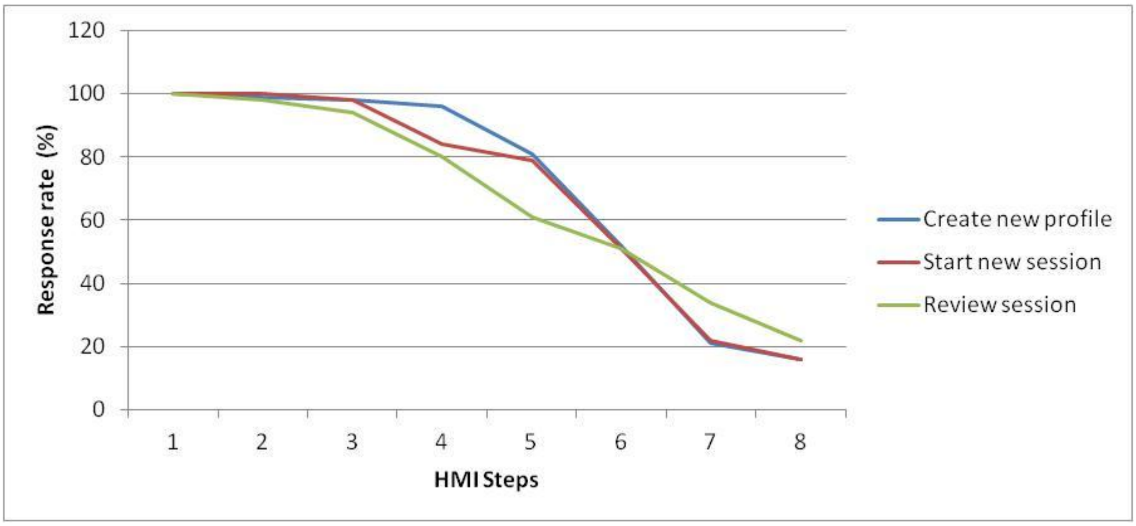


Figure 8.18 Summary of the HMI task analysis questionnaire results which indicate a rapid decrease in user response rate as the number of HMI steps increases.

8.2.7 HMI Storyboarding

The task analysis results were used to design the software structure using a HMI storyboarding technique (Schneidermann 2004). This is an important design process as it refers back to the user requirements and focuses the developer on reducing the number of HMI functions the user needs to accomplish their requirement. The fewer tasks required, the more usable and desirable the system is. Consideration of the different user types is fundamental to this process, as mapping the navigational path specific to the user increases the usability of the system. This HMI storyboarding technique has been applied to the weightlifting domain using the software requirements collected at each stage as shown in Figure 8.19.

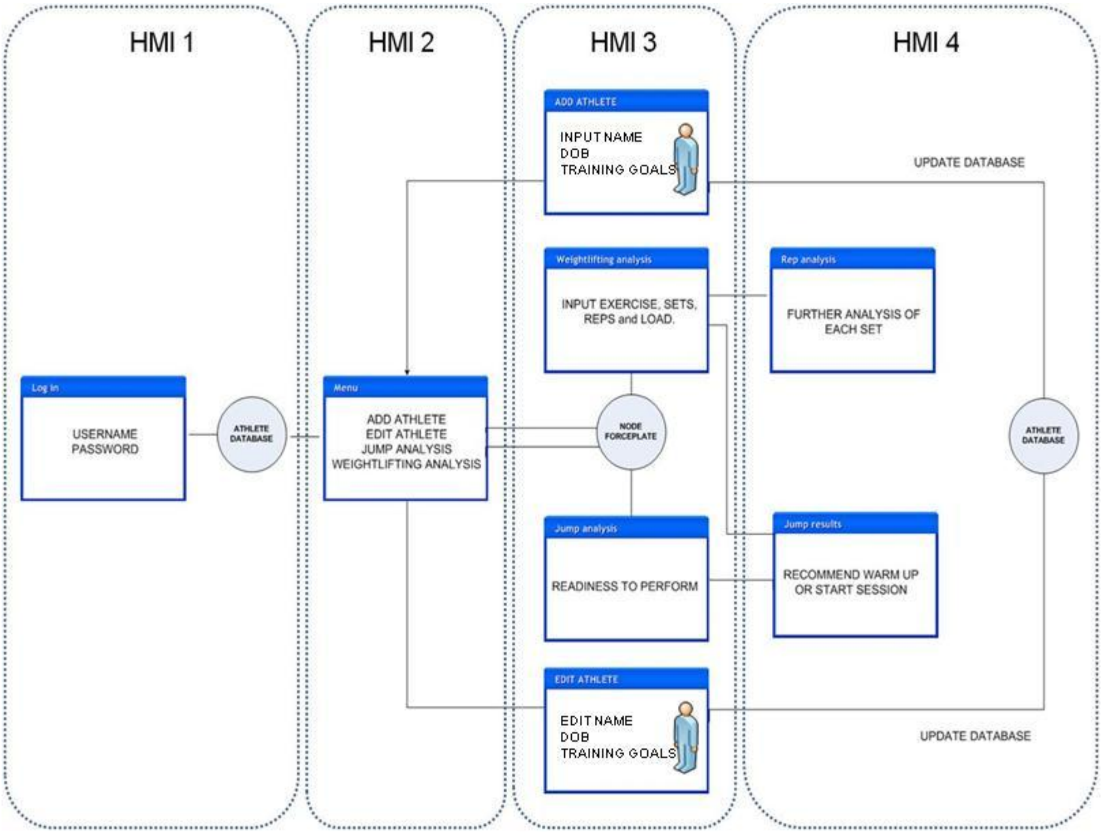


Figure 8.19 Example of the HMI storyboarding technique applied to the resistance training domain.

The aim of the structure presented is to reduce the number of HMI tasks the user needs to perform to reach the desired screen. The athlete details are retrieved from the athlete database following the log in. Storing vital statistics such as the athlete weight, allows the forceplate to be zeroed without having to input the athletes weight. A balance needs to be found in order to communicate accurate data and provide multiple functionality. In order to view detailed information whether using the jump or weightlifting analysis, the user needs to advance to another screen. The immediate feedback is the first screen the user interacts with following the analysis type selection.

8.2.8 HMI consolidation

The final stage of the design involves consolidation of the HMI screens and implementing the software structure. The examples presented in Figures 8.20-8.22 are the initial software structure design prototypes. This structure provided a foundation upon which the software was developed. The aim was to ensure that navigation through the system did not exceed interaction with more than four screens before reaching the desired interface, whilst reducing the user inputs. The user requirements derived from the initial requirements elicitation process (Chapter 4) and hardware testing were also considered.

Validating the software design against the user requirements is a fundamental part of the proposed design methodology. The user requirement corresponding to the identified functionality is documented in Table 8.4. The user requirements evaluation indicates that the prototype software fulfils each of the requirements, therefore suggesting that the design methodology was successful. However, flexibility is a key component of the methodology, therefore the success cannot be judged on the ability to enable hardware and software design in the resistance training domain. Whether the methodology can be applied to another sporting domain is required to determine the flexibility. True value lies in the ability to apply a structured design process to hardware and software development across multiple domains. As a result, a case study was conducted to investigate whether the combined methodology can be used to support software design in another sporting domain. The case study is documented in the following section.

User requirement	Screen
Choice of graphical display	B1.1, B1.2
Review data	C1,
Monitoring of training inputs	A2
Timer functionality	A2.1, B1, B1.2
Feedback between sets	B1, B1.1, B1.2, C2, C2.1,C2.2, C2.11, C2.21, C3
Manual rep selection	C1
Rep calibration	A2, A2.1, A2.2, A3
Force platform and WIMU data	A1
Jump analysis functionality	A1, D1, D1.1, D2
Compare sessions	C2, C2.21, C2.11, C2.3

Table 8.4 Identification of the software requirements and corresponding HMI screens.

Figure 8.20 Software prototype: the HMI screen navigation designed to set up for a weights session.

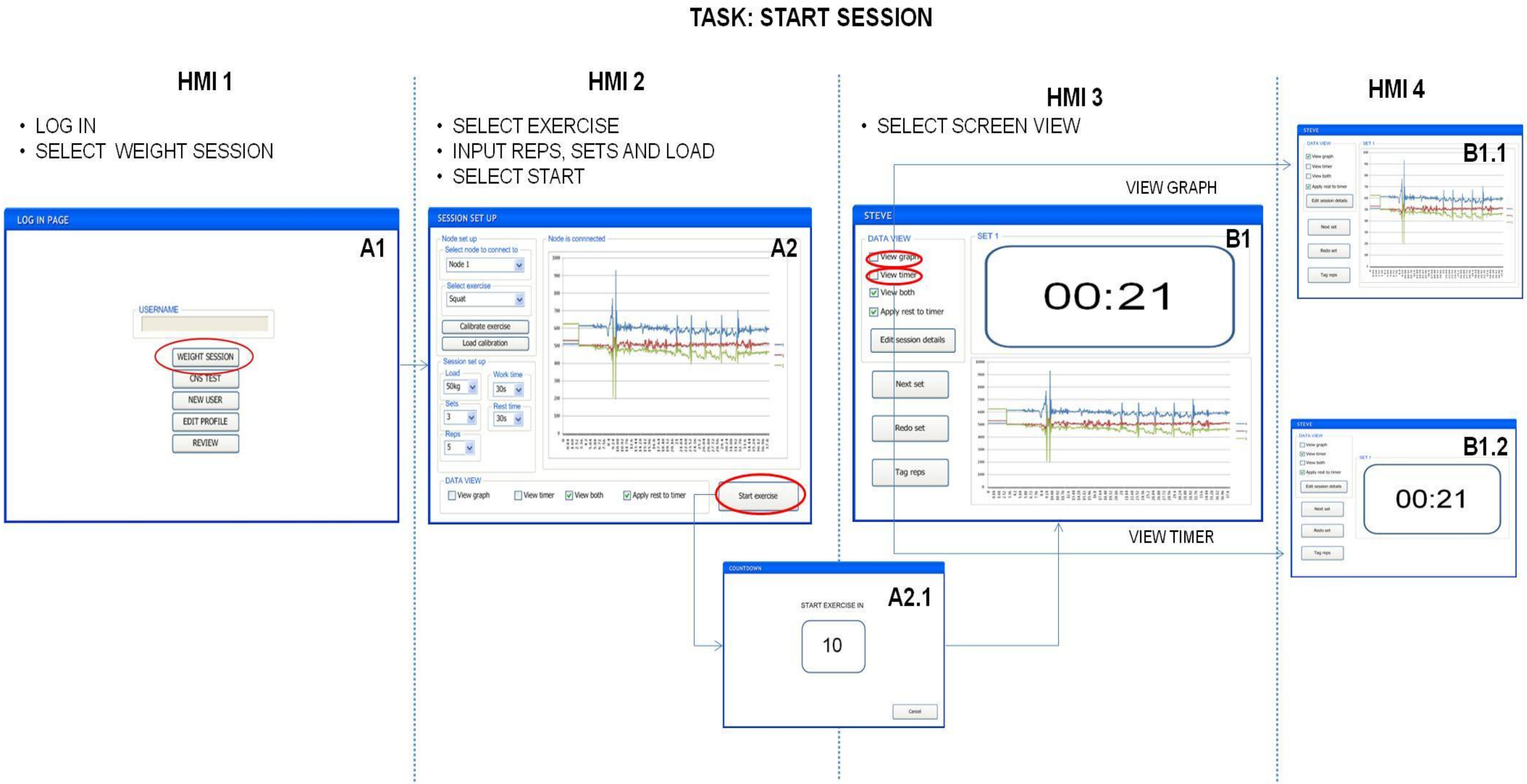


Figure 8.21 Software prototype: the HMI screen navigation designed to start a session

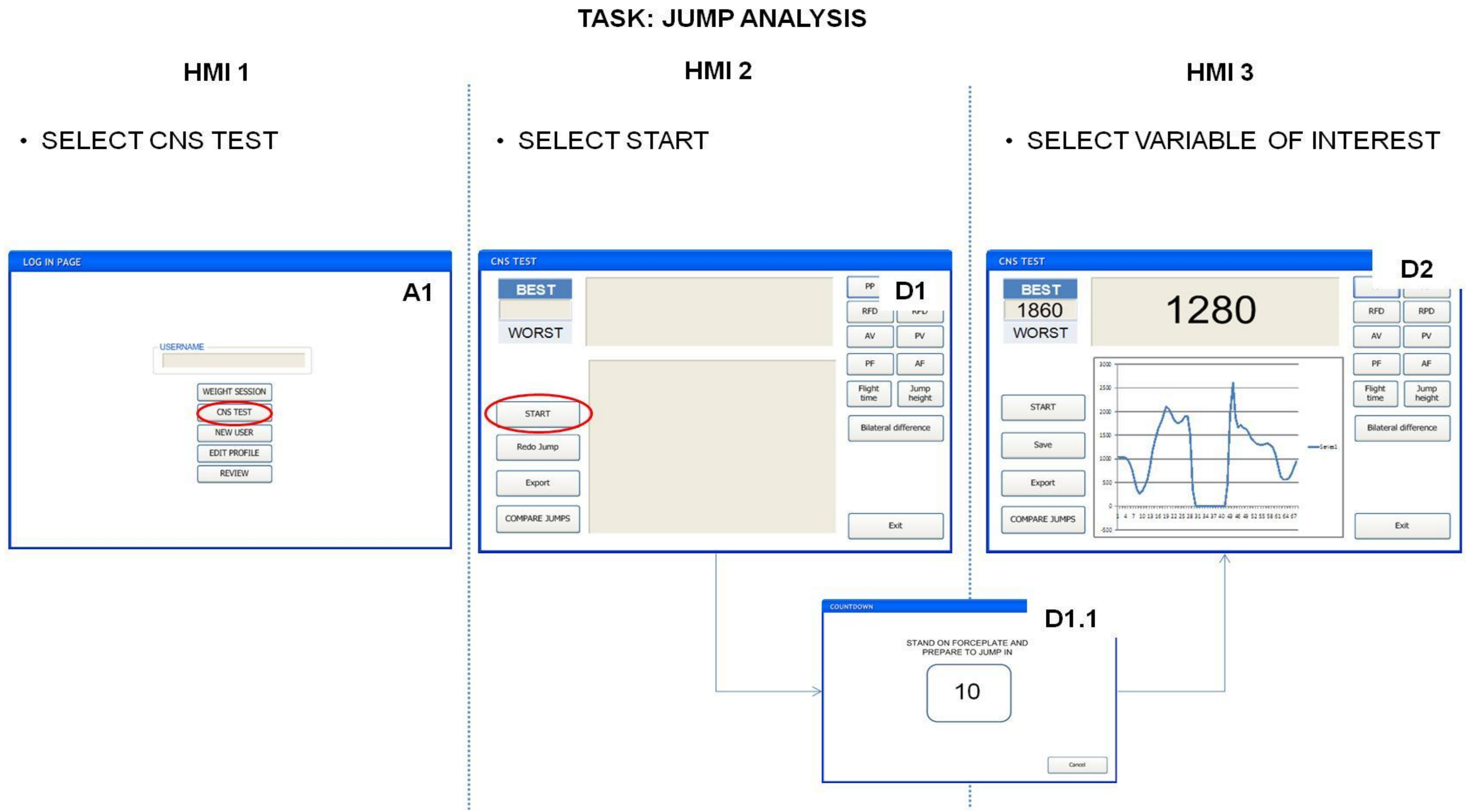


Figure 8.22 Software prototype: the HMI screen navigation designed to accommodate jump analysis functionality.

8.3 Case Study: Application of the combined methodology to another sporting domain

Re-usability of software design is of most use to a designer (Monfared et al 2002, Rahimifard and Weston 2007). Having developed and implemented an iterative design methodology for a performance monitoring system within weightlifting, the next challenge was to investigate the methodology flexibility (as identified in Figure 8.23).

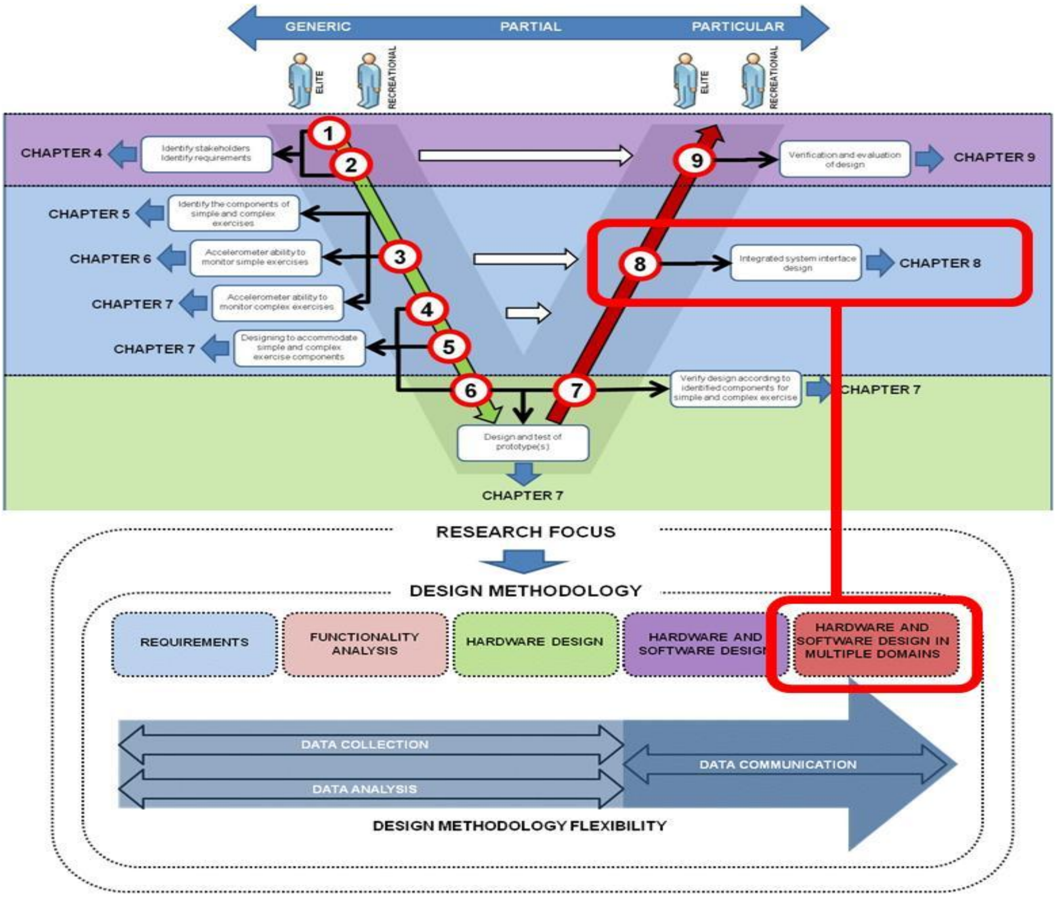


Figure 8.23 Investigating the flexibility of the design methodology by applying the methodology to another sporting domain.

Maintaining focus in the sporting domain means that the *partial* of design level (i.e sports monitoring (see Chapter 2) remains the same, however, the *particular* domain has been changed from weightlifting to swimming. The same wireless technology has been applied to the swimming domain. A non-invasive component-based integrated system, using wireless sensor nodes for monitoring elite swimmers is being developed at Loughborough University (Le Sage 2010). This comprises of non-invasive wireless sensor nodes, wireless data transfer, a vision analysis system using a high speed video camera and real time automatic image processing components.

The aim of the integrated system is to collect multiple swimming parameters in real time, provide feedback to the relevant stakeholders and record them simultaneously for further analysis. Thorough feasibility testing and successful development of prototype product designs means this system is at a different stage of the system development life cycle. In contrast to weightlifting, this design process does not require documentation of hardware development and analysis. It is the communication of the data to the user which currently provides a barrier to use, therefore the design life cycle has a different starting point. The aim of this section is to apply the iterative design approach to the swimming domain, focusing on the design of software to communicate the functionality of the technology.

8.3.1 Differences in application

Designing a monitoring system for the resistance training domain required the consideration of users from the recreational user to the elite to determine how the sophistication of technology would need to increase. The product was also intended to be a gym environment in which the user operating the system is also performing the exercise. The swimming domain was chosen as the operator is likely to be different to the user performing the exercise. The operator will not necessarily differ in level of understanding but more intended use. The aim of the Graphical User Interface (GUI) in this case study is to provide a general performance monitoring tool that considers more than data collection alone. This GUI tool is required to act as a main source of communication between the sports scientists, coaches and athletes. Consequently, the design must consider not only different user types but also their likely interactions dependent on their intended use.

The weightlifting system will be located in an environment accessible to both elite and recreational performers, therefore the interface must accommodate differences in understanding. In contrast, the swimming application will be used by sports professionals and elite athletes, the log in details must be used to restrict access accordingly. The aim is to provide a navigation path through the software specific to the user level. Such contrasting applications have been selected in order to investigate fully the flexibility of the proposed methodology.

A summary of the differences between the swimming and weightlifting domain is presented in Figure 8.24. The subsequent application of the methodology to the swimming domain is documented in the remainder of the chapter.

DIFFERENCES BETWEEN DOMAINS

	WEIGHTLIFTING DOMAIN 	SWIMMING DOMAIN 
TECHNOLOGY	WIMU and force platform technology	WIMU
OPERATOR	Performer does operate the system	Performer does not operate the system
USER ACCESS	All users can access the same information	User distinction using log in details to restrict access
ACCESS	Designed for elite but also used by recreational users	Designed for elite and used by sports professionals
USER	Designed for elite but also used by recreational users	Designed for elite and used by sports professionals
COMMUNICATION	Wall mounted monitor, touch screen	PC screen

Figure 8.24 Differences in between the weightlifting and swimming domain

8.3.2 User requirements

The first step involved collecting data from the user types. Rather than using a questionnaire, data was collected using interview techniques. The stakeholders identified in the elite sports monitoring domain are listed below:

- Athlete
- Bio mechanist
- Nutritionist
- Strength and Conditioning Coach

Conducting numerous interview techniques with each user type generated a list of user requirements listed in Table 8.5. The next step involved combining related patterns into sub-themes, these themes were identified by bringing together components or fragments and establishing the links.

Requirement	Detail
Multi-tier application	A multi-tier architecture (often referred to as n-tier architecture) is a client–server architecture in which the presentation, the application processing, and the data management are logically separate processes.
User friendly	The tool should be simple and intuitive to use. The number of operations should be minimized.
Capture/Visualization capability	The tool should allow the end user to store the session data into persistent storage and also display the session statistics in the display device.
Choice of delivery	The tool should allow the user to view the measurable statistics in a graphical or a tabular manner.
System integration	The tool should be able to integrate other data streams such as video
User level distinction	User operations should be masked based on the level of the user. For example, the sports scientist should be responsible for configuring the teams, sessions, review session data etc. The athlete should be allowed to view only their individual session history and training calendars.
Session Planning	The GUI should allow the sports scientist to create the session plans ahead of the actual sessions.
Sensor identification	Every athlete has a sensor attached to them. The sensor – athlete mapping configuration has to be done before the GUI starts to display or store live sensor data.
Post session analysis	The raw sensor data will not make much sense to the end user. The GUI should do a post processing before the data is presented to the end user. For instance, in the case of swimming, stroke counts, lap counts would make more sense in comparison to raw accelerometer data.
Measurable performance parameters	The post processed data should be presented to the user on real time analysis as well stored into persistent storage for post session analysis
Selective analysis of data	The end user should be able to choose to view all or a few measurable quantities
Athlete Diary	The tool should be able to review and update competition diary, nutrition diary, training diary, hormone diary etc.
Database storage	Relatively large database memory should be available
Changeability	In practice, it is expected that some of requirements might change during development and post release. The design should be able to deal with changes effectively.

Table 8.5 List of software user requirements in the swimming domain.

8.3.3 Systems analysis

To support the GUI requirements definition phase, a detailed systems analysis was conducted to fully understand the flow of data within the swimming environment from a user and system point of view. Complete systems analysis integrates process and data modelling whilst building a strategy for a complete and accurate requirements specification. This is required when developing an interface as it encourages the developer to consider the interface and database structure needed to accommodate the data flow, their directions (sent or received) and any communicative issues that need to addressed by the subsequent domain classification. The context diagram presented in Figure 8.25 provides an understanding of the overall current system.

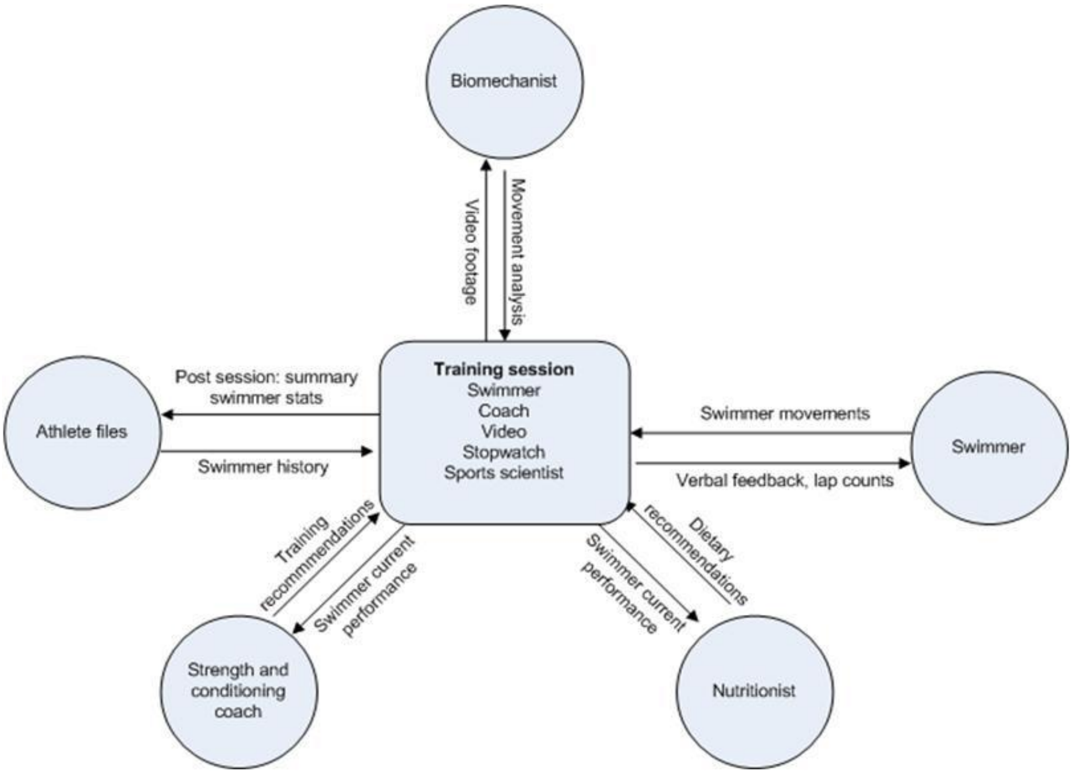


Figure 8.25 Context diagram of the swimming performance monitoring domain

8.3.3.1 Systems analysis of the current system

An inevitable effect of introducing a new system is a change in data flow and data type available to the user. The data flow within the current swimming training environment is illustrated in Figure 8.26. The internal entities are shown within the dotted circle. The arrows refer to the direction of data flow. The current environment does not allow for regular referral to athlete summary statistics and the coach must rely upon verbal communication only. The sport scientist must manually input athlete data which is time consuming and increases the likelihood of human error. There is no official record of swimmer attendance and the swimmer does not play an integral role in the data analysis or feedback system. Communication between all sources is reliant upon verbal communication and there is no central system to which the sports professionals and athletes have access to review past and current performance.

8.3.3.2 Systems analysis of the new system

In order to understand the data flow effect, the same process was applied to the proposed system. The increase of data sources within the training session directly impacts the data flow. Directional arrows are used to improve communication channels between entities. The context diagram for the proposed system is illustrated by Figure 8.27. The inclusion of an athlete database and the GUI application allows the data to be accessed from a variety of sources. The central database ensures that the sports professionals and athlete can view past and present performance data. The GUI provides real time data that can be communicated within a session, minimising the coach's reliance upon verbal communication. The functionality to store and review WIMU, force platform and video data increases the performance knowledge that can be gained for each athlete during and post session. The structure of the GUI and the supporting database will directly impact the overall perceived usefulness of the system. Using the proposed data flow context diagram and considering the user requirements, the developer can identify the domains within the GUI to accommodate the data flow.

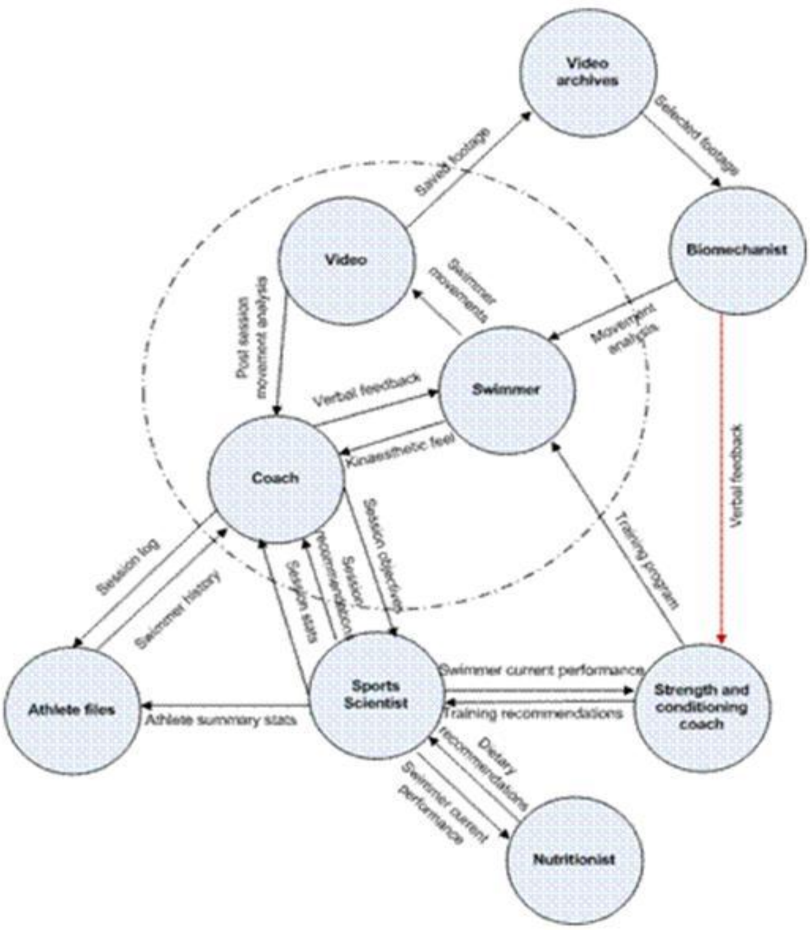


Figure 8.26 Data flow within the current swimming environment

Figure 8.27 **Data flow within the new swimming performance monitoring environment**

8.3.4 Domain Classification

Domain analysis and classification was conducted using the user requirements (Table 8.5) and systems analysis to determine the sub themes. In contrast to the weightlifting application, there is a desire to incorporate the external aspects to training so that all the sports professionals within the elite swimming domain can benefit. The aim is to increase quantitative feedback in the session using immediate feedback and also after the session through post analysis. The domains chosen for the GUI functionality and subsequent domain processes within each domain are listed in Table 8.6.

Enterprise Domain	Domain Name	Domain Process	Explanation
DM1	Real time monitoring	BP1.1	Data collection set up
		BP1.2	Display measurable variables real time and post process raw accelerometer data into more meaningful information like stroke count, lap counts etc.
		BP1.3	Choice of delivery – graphical or tabular
DM2	Data storage	BP2.1	Login access validation
		BP2.2	Store data to database
		BP2.3	Retrieve data from database
DM3	Post session analysis	BP3.1	Retrieve user data
		BP3.2	Display performance parameters
DM4	Settings and configuration	BP4.1	Configure resources
		BP4.2	Configures sessions
		BP4.3	Configure hardware – sensors, force plates
		BP4.4	Save configuration to database
		BP4.5	Export session configuration to pdf
DM5	Biomechanical and nutritional	BP5.1	Other analysts will need to view certain data, effective training stems outside the sports specific training session

Table 8.6 List of domain processes existing within each sub domain

8.3.5 Business process analysis

A level 1 data flow diagram is presented in Figure 8.28, this is a high level analysis taking into account the entities involved and the processes that construct an overall session from beginning to end. Each business process is decomposed further to investigate the enterprise activities present, the breakdown of business process one (BP1) is shown in the Level 2 data flow diagram (Figure 8.29). BP1 focuses on the activities required for planning a session. The complexity of the diagram is increased due to the identification of the database capability required to store and access data table information. This also demonstrates how communication between different analysts (e.g. biomechanist, nutritionist and strength training coach) is required in order to plan and implement an effective training plan.

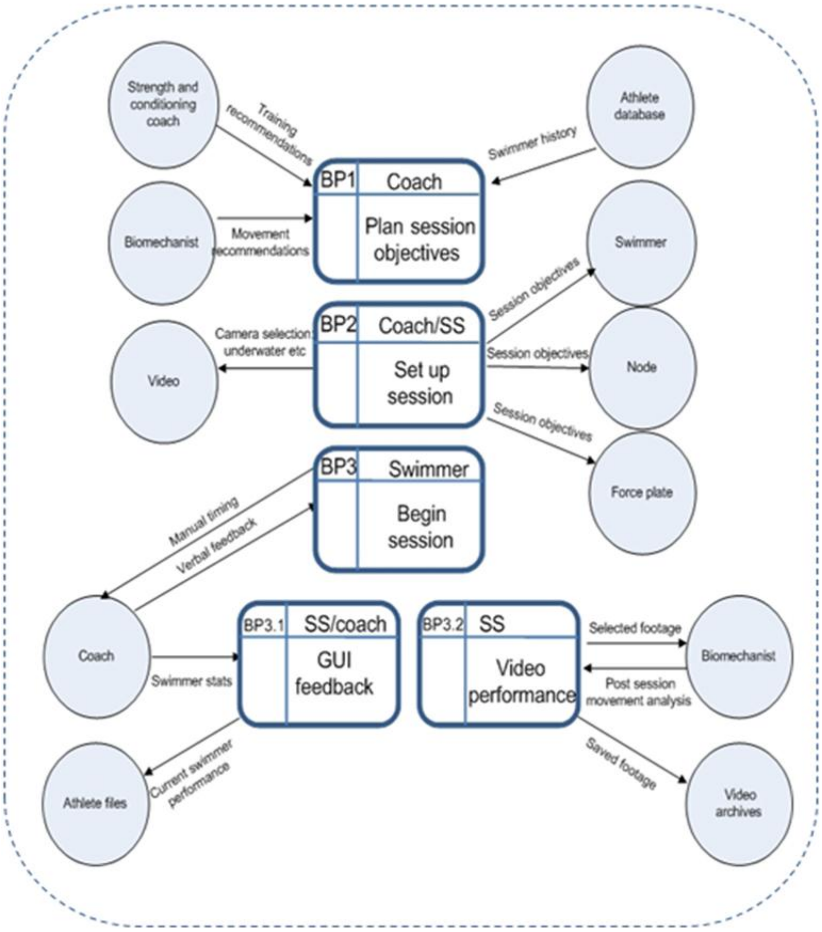


Figure 8.28 Level 1 document flow diagram of the proposed system business processes and relationship to internal and external entities.

The data flow sequence required for the configuration of the external monitoring devices (e.g. WIMUs, video cameras and force platforms) and the session data capture within BP2 and BP3 is demonstrated in Figure 8.30. This involves recording accelerometer data using the WIMU (as per Chapter 7) both over and under water video cameras and force plates. The coach/sports scientist configures (or calibrates if necessary) the sensor nodes before the start of a training session. Either of the above mentioned user types is responsible for determining the physical mapping between the WIMUs and the swimmers and also for configuring the external monitoring devices for the data capture. Once all the devices are active, the data capture can be started using a trigger mechanism. The GUI software displays in real time the sensor data, video footage and the force platform data. The coach/sports scientist can instruct the GUI to start or stop recording the desired session data into database tables. The deactivation of the hardware devices will stop any data from being displayed on the software or being stored in the database.

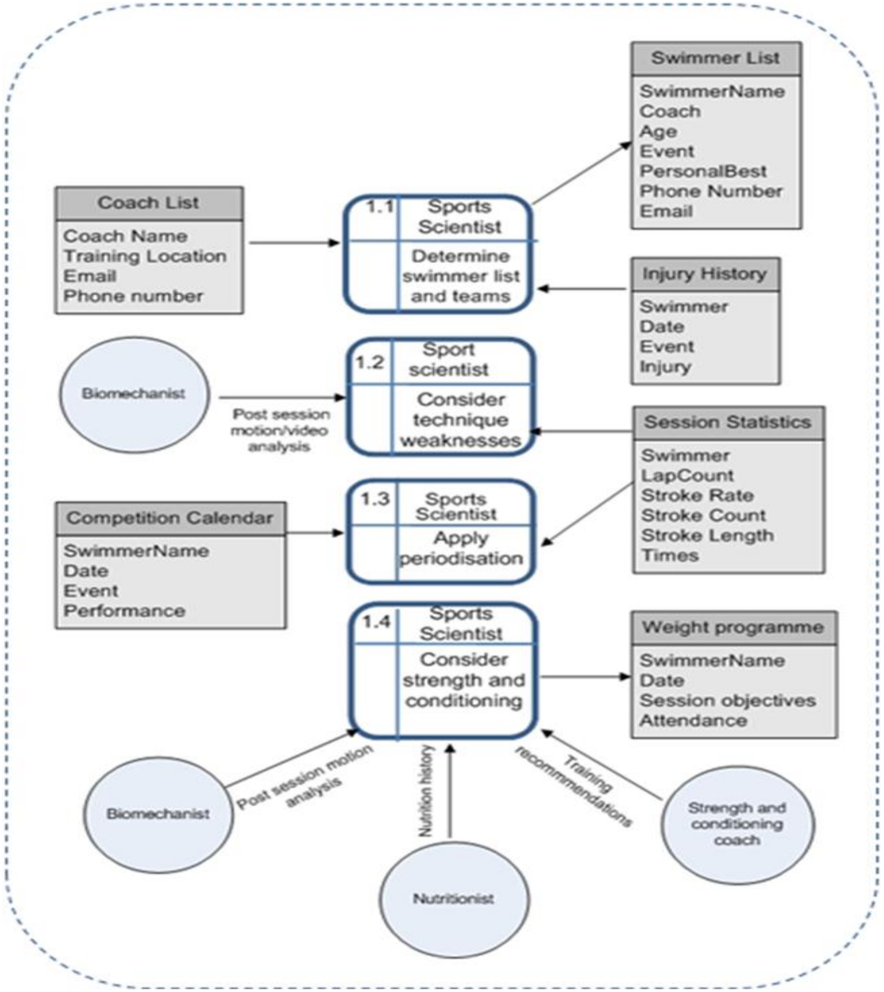
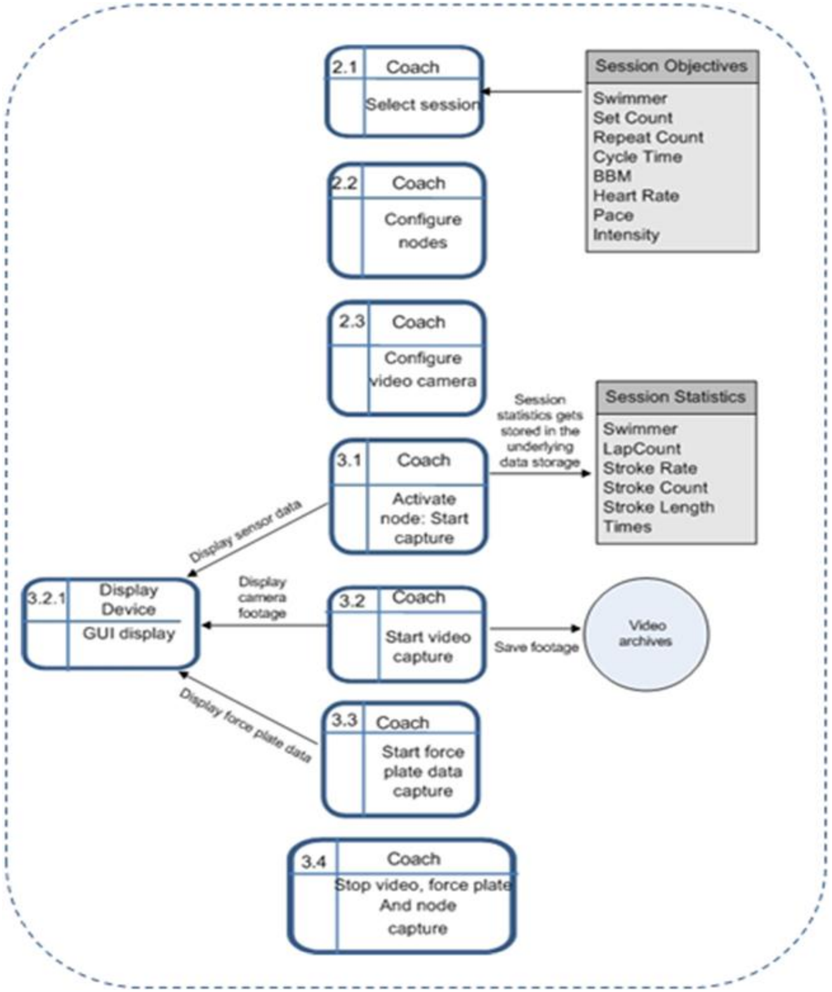


Figure 8.30 Level 2 data flow diagram breakdown of BP1



Level 3 Figure 8.29 data flow diagram breakdown of BP2 and BP3.

8.3.6 HMI task analysis

The aim of this process primarily involves the design of the screens the user will interact with and determining the relationship between each to help identify any areas where the user has to input too much data or repeat a process- both of which reduce the usability of the system. However, often this process does not account for the different type of users, relying upon the "generic user" needs to create the navigational path. By referring back to the initial stages in the overall system design process from *generic* to *particular* and brainstorming the order of HMI functions in relation to the user type further increases the usability of the system. Reducing the number of clicks to the screens of highest priority, identified in the user requirements section, demonstrates how this method allows the developer to envisage the path of the user in multiple scenarios.

Coach	Sports Scientist	Swimmer	Biomechanist	Nutritionist	Strength and Conditioning
1. Session Plan 2. Record session 3. Review session 4.Settings and configuration	1. Session Plan 2. Record session 3. Review session 4. Settings and configuration	1. Profile 2. Training diary 3.Review (Individual)	1. Video archive 2. Session plan 3. Training diary	1. Session plan 2. Training diary	1. Session Plan 2. Training diary

Table 8.7 The order of operation according different user types

This process was conducted for the coach, swimmer, sports scientist, nutritionist and biomechanist at the *particular* level. The order of operation each user is likely to take is illustrated by Table 8.7. Brainstorming the navigational paths allows the designer to identify which HMI screens are to be accessed by all and therefore require easy access from all user starting points in comparison to those that are specific to the user. Although the HMI tasks and task order are identified in Table 8.7, storyboarding the navigational path is of more use to the designer as it clarifies the relationships between each type and the most efficient route to take to achieve the needs of highest priority. There is a desire to collect and correlate as many sources of information as possible to identify major influences on performance. The software is not a only a one to one interface, it is a one to many, being able to store and view data from different sources to create a "bigger" picture through a "training diary" has a major impact on the software design.

8.3.7 HMI Navigational paths

The proposed method of HMI task application, by using a storyboard technique to distinguish the order of tasks identified in Table 8.7 is presented in Figure 8.31. It is much clearer to the designer which screens can be replicated and reused for each user type, improving the efficiency of the design process. The "widgets" illustrate the buttons used to access each screen, for example, being able to create a session plan is required by multiple users, although their plans will be different, the generic format of the session plan screen can remain the same throughout the system. This screen can be used as a major communication tool, allowing each user to view the date and type of training already planned for each swimmer, whilst reducing the design time in creating multiple screens specific to the user, which fundamentally have the same purpose.

The aim is not to identify HMI tasks and create screens to target each individually, it is more to identify areas where functionality is shared between user types and distinguish the different order of tasks. Creating user specific navigational paths is of more use to both the user and designer in improving the usability and intuitive nature of the system. Furthermore, routes that force the user to complete too many tasks are easily identified. The designer should aim to decrease the number of screens at each HMI level. Only two HMI screens are present at the fifth HMI level as illustrated in Figure 8.31. Although 5 "clicks" may seem too high, this only applies to the users who are required to configure the system and have increased functionality.

A compromise must be made between providing such functionality and reducing the HMI levels. Reaching these same screens but at an individual level can be achieved by the swimmer within four clicks. This is a good example of shared functionality but via a different route that increases the usability specific to user type. The implementation of the storyboarding technique to create prototype software is presented in Figure 8.32. The session plan screen provides a joint communicative base, this reinforces the principles of training across domains, whether the planned session is set by the coach in the water or by the strength and conditioning coach in the gym, the same principles apply. Although individually each coach may be planning an effective training programme, if they are not aware of the demands being placed on the swimmer in other sessions, overload is likely to occur.

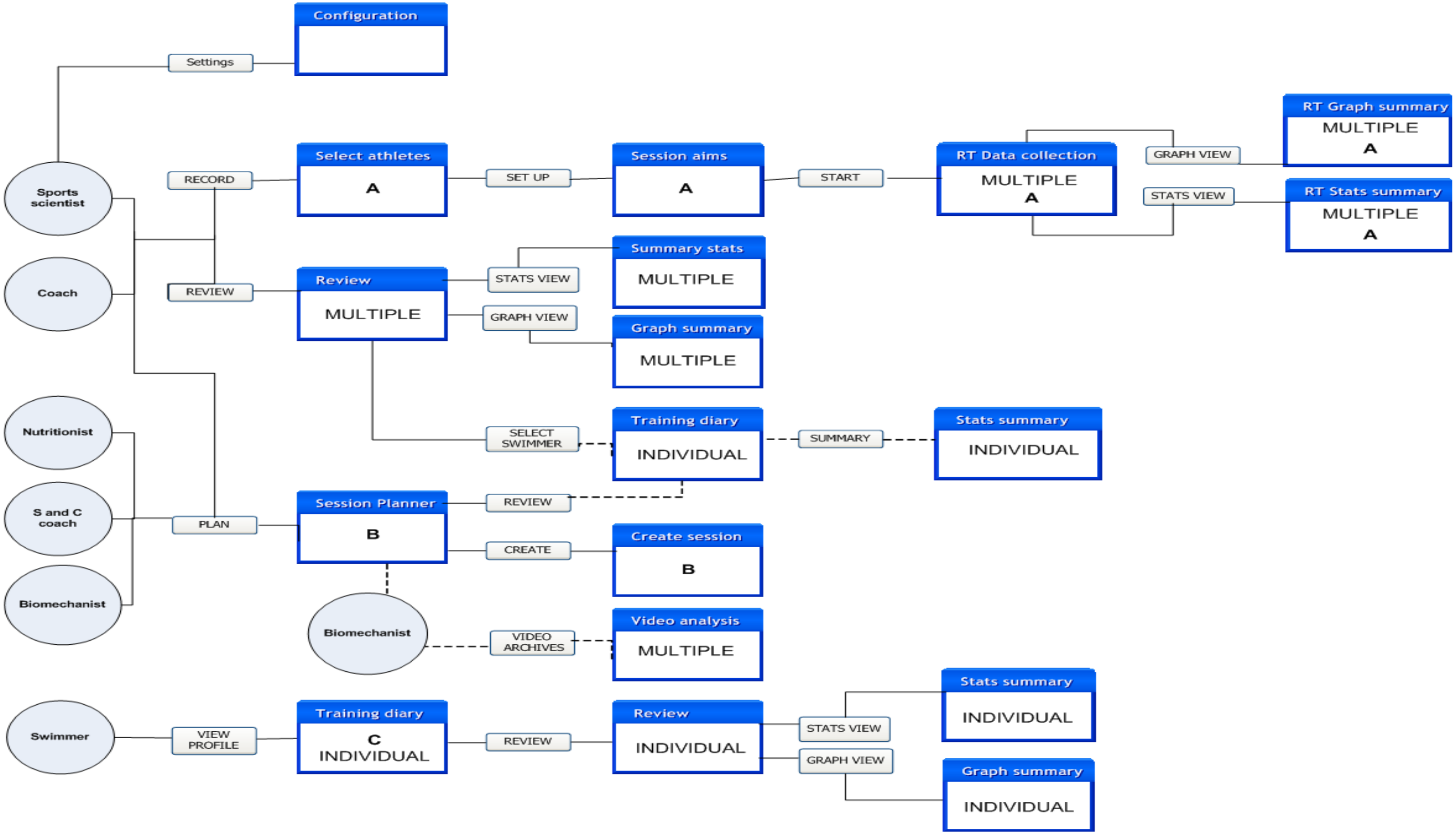


Figure 8.31 HMI storyboarding used to determine user specific navigational paths in the swimming domain

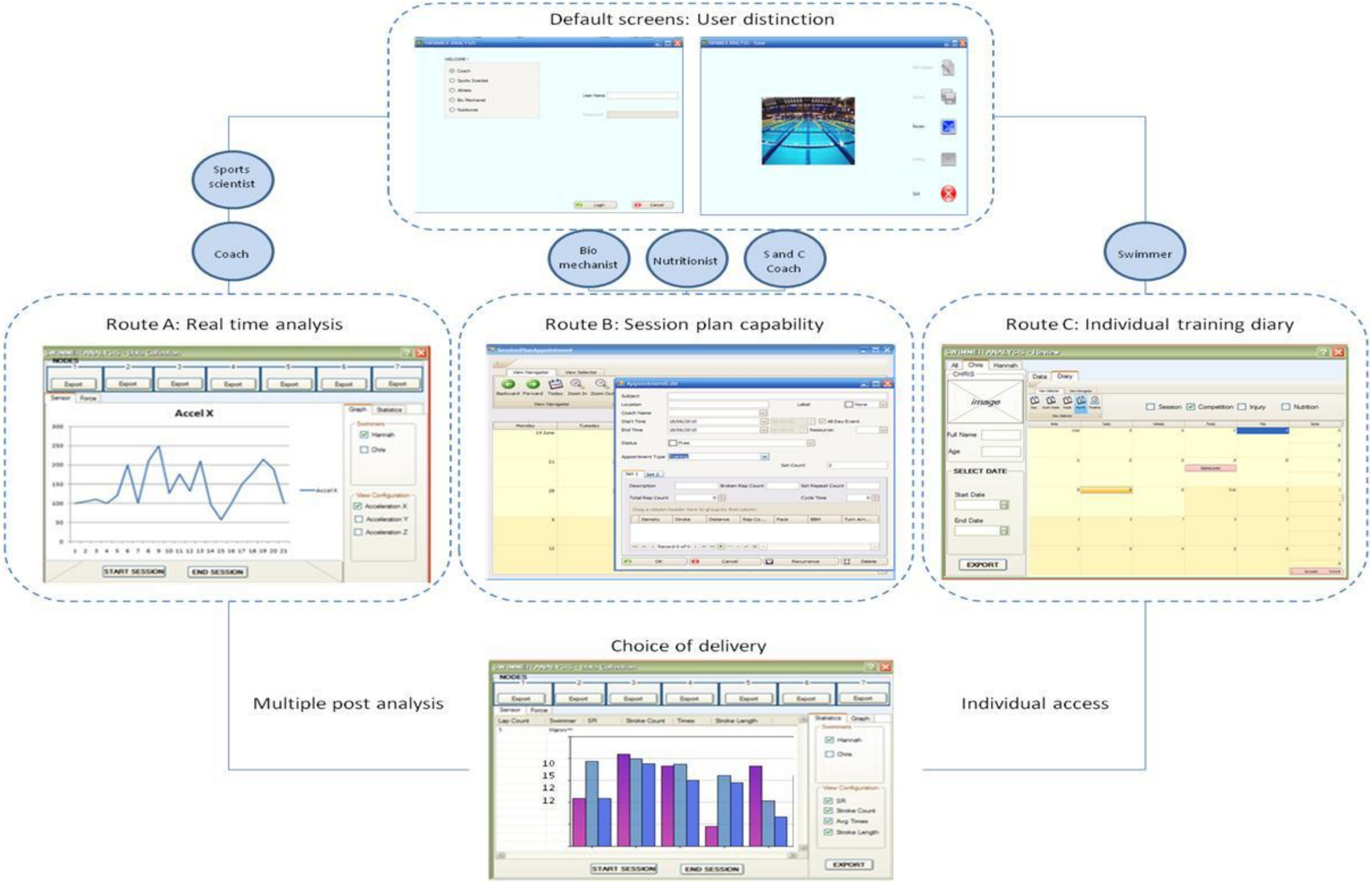


Figure 8.32 Implementation of HMI storyboarding navigational paths in the swimming domain

Similarly, the nutritionist needs to be aware of the demands being placed on the swimmer in all training sessions in order to meet fully the individual needs. Providing a generic session plan HMI screen also simplifies the system design process as each user will access this one screen but with restricted editing capability. For example, the biomechanist can only alter the biomechanist session yet they can view the planned sessions set by the sport scientists.

Each swimmer analyst can access a swimmers individual training diary from this session plan based upon the date and selected swimmer. This further supports targeting the individual needs of the swimmer. This path is suited to the nutritionist, biomechanist and strength and conditioning coach as they do not need a direct link to data analysis and so can view swimmer results by accessing the training diaries first. However, both the coach and sports scientist will often analyse swimmer results as a group and individually, therefore providing a "short cut" to a "review page" decreases the number of HMI tasks they have to complete and again increases the usability. Using this method the developer is forced to reconsider the importance of the user and user types, demonstrating the iterative nature and user focus. The fulfilment of the software user requirements using the current and new system is presented in Table 8.8. The results indicate that the new system design meets all the specified user requirements. Therefore it can be concluded that the design methodology is flexible and can be readily applied to other sporting domains.

Requirement	Current system	New system	Status
Multi-tier application	No	Yes	Tested
Real-time feedback on stroke rate and lap count	Yes – verbal only	Yes	Tested
User friendly	No – time consuming	Yes	Under enhancement
Capture/visualization capability	No	Yes	Tested
Choice of delivery	No	Yes	Tested
System integration	No	Yes	Under enhancement
User level distinction	No	Yes	Tested
Session planning	Yes – manual notation	Yes	Under enhancement
Sensor identification	N/A	Yes	Under enhancement
Post-session analysis	Yes	Yes	Tested
Selective analysis of data	No	Yes	Tested
Athlete diary	No	Yes	Under enhancement
Database storage	Yes	Yes	Tested
Changeability	No	Yes	Under enhancement

Table 8.8 Comparison of the current and new system in relation to the identified requirements.

8.4 Brief Chapter summary

TARGET OBJECTIVE:

To apply the proposed combined methodology to design supporting software for an elite based performance monitoring system and determine the flexibility of the proposed combined methodology.

TARGET RESEARCH QUESTIONS:

Can the combined methodology be applied to the software domain?

When applying the combined methodology to the software domain, there is more focus upon the decomposition of the system requirements using the identified modelling approaches rather than testing. Hardware testing must be conducted before software design can begin as the product capability must be well understood. The data flow within the current system and the proposed data flow must be considered to prevent data redundancy.

How does the combined methodology promote user-centred design?

The user requirements are re-iterated throughout the process, investigating the data flow within the environment considers how data is currently communicated to derive how the new system should communicate data to the user. HMI task analysis, storyboarding and consolidation ensures that how the user interacts with the system and user navigation is considered. The derivation of system requirements from user requirements ensures that all functionality is relevant and the system is not over complicated.

Is the design methodology flexible?

The methodology was successfully applied to the swimming domain in which the system requirement were significantly different. The reference architecture enabled the software design to progress from a generic to particular level using each step in the methodology. The designed software targeted each user requirement and supported user distinction to restrict user access using the same methodology applied to the weightlifting domain. This suggests that the methodology can be applied to numerous domains to support both hardware and software design.

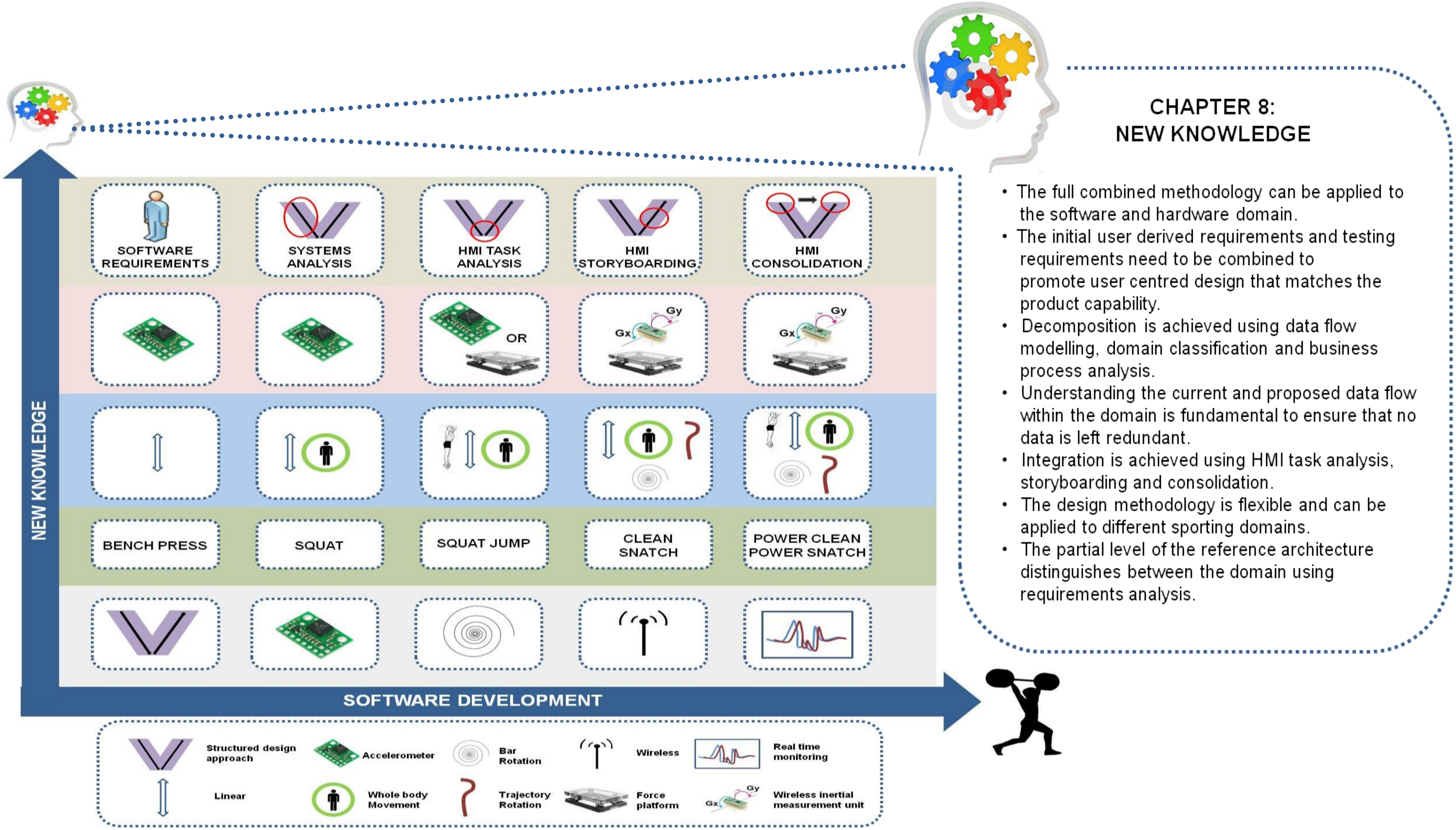
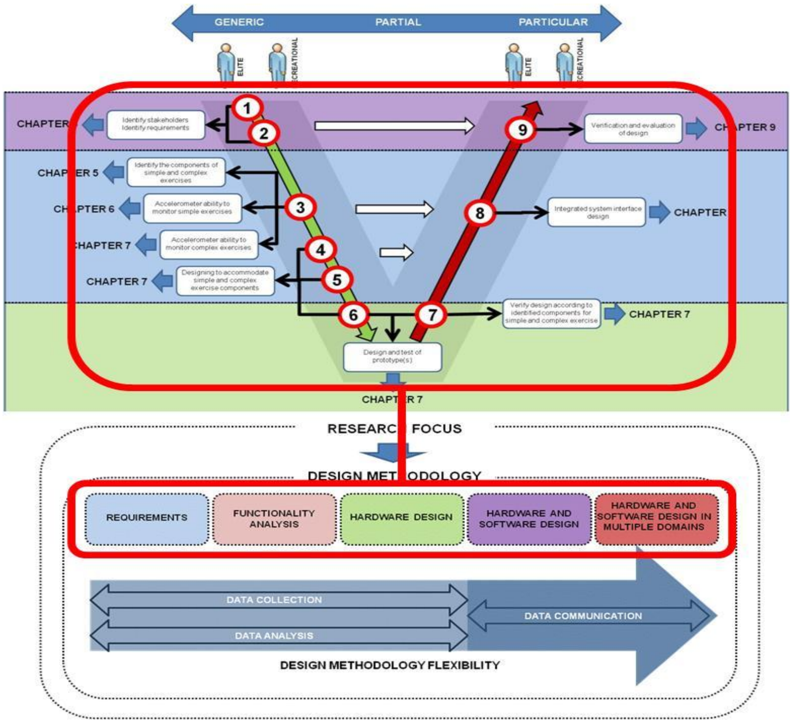


Figure 8.33 The identification of new knowledge acquired and core question findings: The combined methodology can be applied to promote user centred software design and communicate the data to the user effectively.



Chapter 9

9.0 Conclusions and future work

9.1 Research summary

The overall aim of this research was to investigate the promotion of user centred design in the sporting domain focusing on the development of technology within the resistance training domain based upon the primary research question listed below:

How should hardware and software design and development be implemented in the sports domain to facilitate performance understanding and accommodate changing user requirements?

The research had to consider three elements to develop, apply and validate a user centred design methodology. The research was split into the three categories listed below:

- *Development of a user centred design process methodology for the sporting domain.*
- *Application of the methodology to design a user centred, elite based, performance monitoring system for the resistance training domain.*
- *Application of the methodology to the software domain and another sporting domain to investigate the flexibility of the proposed methodology.*

9.1.1 Developing the user centred design methodology

The design methodology was structured to target the main elements required to promote user centred design (illustrated in Figure 9.1). Chapter 2 focused upon the evaluation of current enterprise modelling techniques and systems process models to identify the most user centred, systematic, iterative and flexible modelling components. Rather than selecting one to use in isolation, several models and modelling approaches were combined. The methodology was based on the reference architecture supported by the CIMOSA framework, the decomposition and integration framework supported by the "vee model", the iterative nature of the spiral process and data flow modelling supported by systems analysis. Combining the methods promoted user centred design by ensuring the user was involved from the start of the design process and user requirements were re-iterated. The knowledge required to promote user centred design to bridge the gap between the user and developer is displayed in Figure 9.1. The corresponding methodology step designed to acquire that knowledge and application to the resistance training domain is also identified. The structure indicates that the methodology incorporated all the user centred design elements.

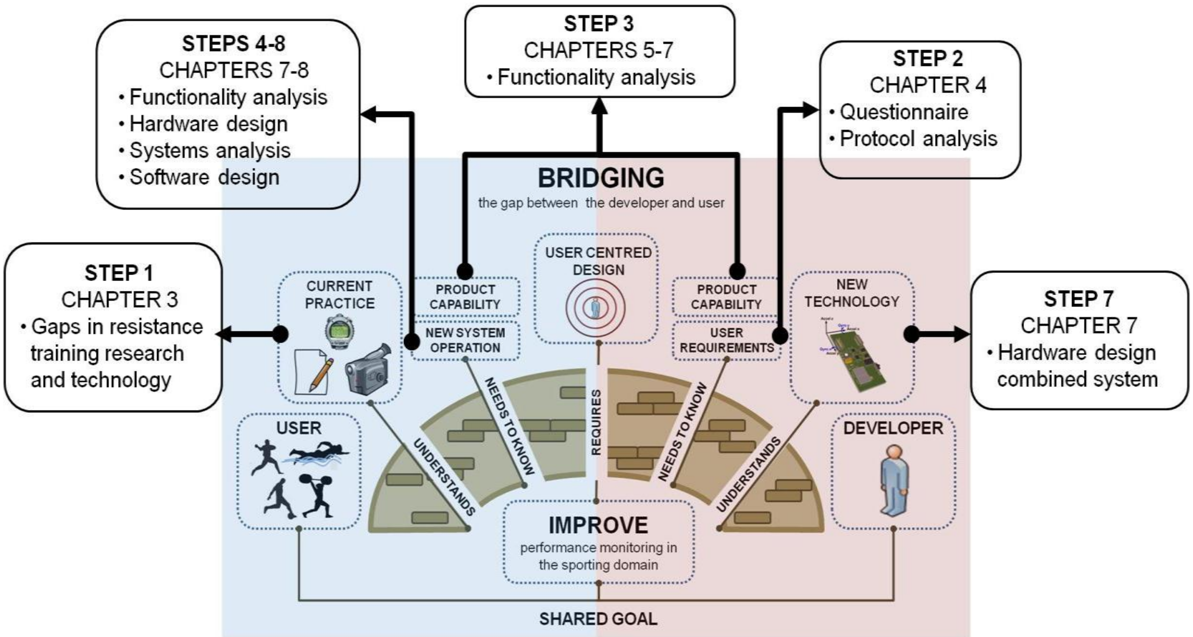


Figure 9.1 The elements required to promote user centred design and identification of the corresponding design methodology steps used to target each one.

9.1.2 Application of design methodology to the resistance training domain

The design methodology was then applied to the resistance training domain to design a user centred, elite based performance monitoring system. In order to apply the generic sporting domain design model to the resistance training domain an understanding of the domain and the current gaps in technology and research was required.

Therefore, Chapter 3 was focused on providing a thorough literature review to develop an understanding of the technology and research limitations. The results indicated that most research focused on the monitoring performance using video and force platform analysis. A review of the current literature indicated that few studies had been conducted investigating the capability of accelerometer and WIMU technology to monitor performance in the resistance training domain. Of the studies conducted, research was limited to linear exercises (Chang et al, 2007) or did not consider the effect of rotation inflicted during complex exercises (such as the power snatch) (Sato et al 2009). The significant lack of monitoring technology suitable for the gym environment and corresponding user requirements also indicated that there was a need to increase research regarding accelerometer and WIMU development. Research documenting accelerometer application did not investigate the effect of rotation occurring during more complex exercises. Real time analysis was not available in a gym environment, therefore users relied upon manual notation of training inputs and verbal feedback. At the elite level, the force platform was the most common form of technology used, with the squat jump being the most commonly investigated exercise. There was a need to investigate a wider range of exercises numerous monitoring devices. The results also identified that there was no distinction between simple and complex exercises, in which complexity was based upon the number of key components required to execute the exercise.

Using the identified gaps in research and technology, the design methodology proposed in Chapter 2 was followed throughout the remainder of the research. Chapter 4 targeted steps 1 and 2 by focusing on user requirement elicitation using both observational and conversational techniques. The aim was to investigate both user opinion and behaviour and identify how a user distinguished between simple and complex exercises. Step 3 was followed in Chapters 5-7 to investigate the product capability set. Step 3 formed a major part of the research as hardware development heavily relied upon a thorough understanding of the product capability. Therefore the testing was broken down into simple and complex exercises which followed the decomposition process of the design methodology. The testing was also designed to identify the key components of complex and simple exercises to determine the level of technology sophistication required for the analysis of both simple and complex exercises.

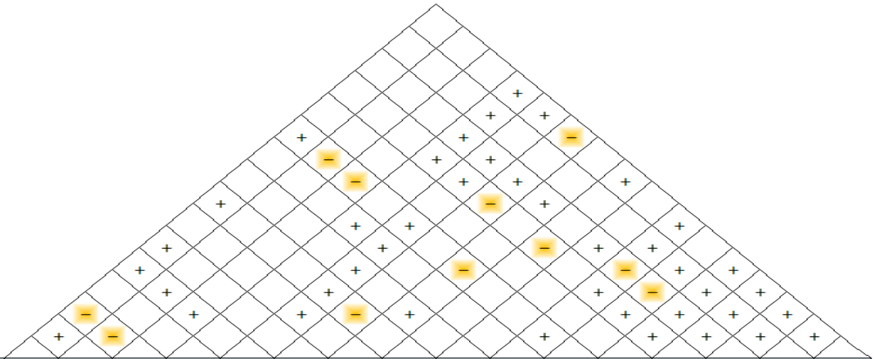
The results of the functionality analysis conducted in Chapters 5-7, were used to generate the design of a combined system capable of monitoring both simple and complex exercises in the resistance training domain. Chapter 7 focused on the design and development of a combined system that eliminated device rotation and corrected for bar and trajectory rotation, whilst considering both bar and body kinematics for complex exercises. The system included the design of a bar attachment that reduced device rotation and a combination of WIMU and force platform technology to collect both body and bar kinematics. The force platform was designed to monitor bilateral difference using a double plate design.

The collection and analysis of data has been considered in Chapters 3-7 and the communication of data was documented in Chapter 8. The development of supporting software to communicate performance data was achieved using the design methodology. Decomposition of the user and system requirements was achieved through data flow modelling, domain classification and business process analysis. Rather than focusing on functional analysis, testing focused upon user interaction through HMI task analysis. HMI storyboarding allowed the navigation through the system to be considered, ensuring that user tasks could be performed within 5 HMI screens to increase usability. The House of Quality first presented in Chapter 4 was revisited to evaluate the combined system. Evaluation of the overall combined system including hardware and software user and system requirements is presented in Figure 9.2. The results indicate that the new system meets all of the identified user requirements and significantly increases monitoring capability in comparison to other products. The requirements score for the new system is between 36%-61% higher than the three competitors. Therefore, it is concluded that the design methodology successfully facilitated the development of an elite based performance monitoring system suitable for the resistance training domain.

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Row #	Customer Importance	Maximum Relationship	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Customer Competitive Assesment				Row #
			Direction of Improvement	◇	▼	▼	◇	◇	▲	◇	▲	▲	▼	▲	▲	◇	▲	▲	▲					
			Customer Requirements / Functional Requirements	Wireless transmission	Dimensions	Weight	Interface	Technology combined	Sampling rate (Hz)	Withstand high forces	Bandwidth (Mbit/sec)	Durability	Set up time	Suited to a gym environment	Supporting analysis software	Multiple users	Suitable for elite analysis	User friendly	Stroage capability	New system	Myotest	MusclePowerLab	Tendo	
1	10	10	Real time feedback	●				●	●		●		○			○	●	○	●	5	5	0	5	1
2	10	10	Max and average power				●	●		●					●		●			5	5	5	5	2
3	9	10	Max and average force				●	●		●					●		●			5	5	0	0	3
4	8	10	Max and average velocity				●	●		●					●		●		●	5	5	5	5	4
5	7	10	RPD and RFD				●	●		●					●		●		●	5	3	0	0	5
6	6	10	Readiness to perform				●	●		●					●		●		●	5	0	0	0	6
7	8	10	Training input feedback				●	○					●	●	●		●		●	4	0	0	0	7
8	8	10	Variety of exercises	○				●	○	●	○	○	○		○		●	○	○	5	2	2	2	8
9	6	10	Feedback between sets	●			●	●	○				○	○	●		●	○	○	5	4	2	1	9
10	5	10	Choice of graphical display				●	○					○	○	●		○	●		5	3	2	2	10
11	8	10	Bar mounted product	●	●	●		●	●	●	●	●	●	●	●	●	●	●		5	5	5	5	11
12	10	10	No disruption to session	●	○	○	○	●		○			●	●	●	○	●	●		4	4	3	3	12
13	10	10	Comparison between sessions	●	○	○	○	●		○			●	●	●	○	●	●	●	5	3	3	3	13
14	10	10	Bar and body kinematics		○	○	●	●	○	○			○	○	●	○	●		○	5	1	1	1	13
15	10	10	High accuracy	●	○	○	○	●	●	●	●	●	●	○	●	○	●	○	●	5	2	1	1	13
			Max Relationship	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	TOTAL SCORE				
			Technical Importance Rating	10	5	10	8	9	7	8	7	6	7	9	8	5	10	10	9	73	47	29	33	

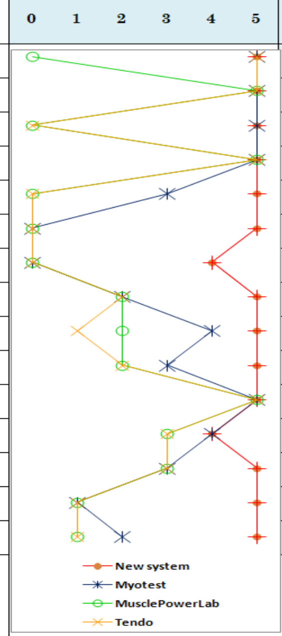


Figure 9.2 Evaluation of the new system using the House of Quality first presented in Chapter 4 to evaluate the ability of the new system to meet the user requirements in comparison to competitor products.

9.1.3 Flexibility of the design methodology

The flexibility of the design methodology was investigated by applying the process to the software domain to ensure communication of performance data was considered. The ability to apply the methodology to another domain was also addressed in Chapter 8 which documented the software design for a monitoring system in the swimming domain using all 9 steps of the design methodology. The extent of the design methodology flexibility is illustrated in Figure 9.2. Flexibility was investigated at the highest level through application to another sporting domain. Evaluation of the weightlifting and swimming software indicated that the user and system requirements had been achieved. This suggests that the design methodology successfully captured user requirements and facilitated the development of supporting software to communicate performance data in both sporting domains. User centred design was promoted in the hardware and software domain and two different sporting domains, therefore, it can be concluded that the design methodology is flexible.

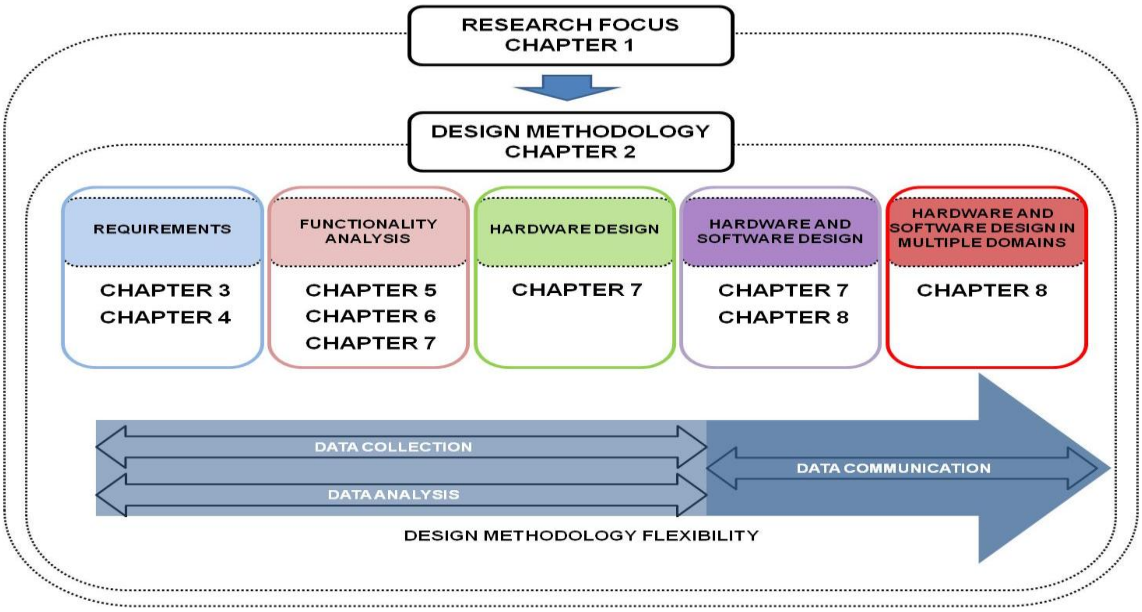


Figure 9.3 Identification of the elements targeted to investigate the design methodology flexibility and the corresponding Chapters.

Overall, the research did not simply focus upon developing a performance monitoring system within the resistance training domain. The research aimed to develop a monitoring system, using a structured and generic user centred design process that could be tailored to the resistance training domain. The flexibility of the methodology enabled the design of both hardware and software to ensure that the collection analysis and communication of performance data was considered. The CIMOSA framework provides a reference architecture that allows developers to work from a general level to specific design. The number of steps and iterative components of the CIMOSA based methodology result in an extensive process that may be simplified within the sporting domain. It is suggested that the outlined methodology should be used as a guideline and the developer may simplify the concept depending upon whether the system is a large multi-stakeholder design or a one-to-one machine system. As the population and user type diversity increases (large multi-stakeholder system), the need to apply the complete CIMOSA methodology from the general to particular level increases due to the need to accommodate multiple changing user requirements and a variety of human-machine interactions. For more bespoke applications, it is suggested that the developer focuses on the particular level of the CIMOSA framework.

9.2 Contributions to new knowledge

At the end of each chapter, a summary of the new knowledge acquired as a result of the research was provided. A number of objectives were outlined at the beginning of each Chapter, these formed the basis of the research to acquire new knowledge. The Chapter target objectives and questions were based upon the core questions identified in Chapter 1, illustrated in Figure 9.4.

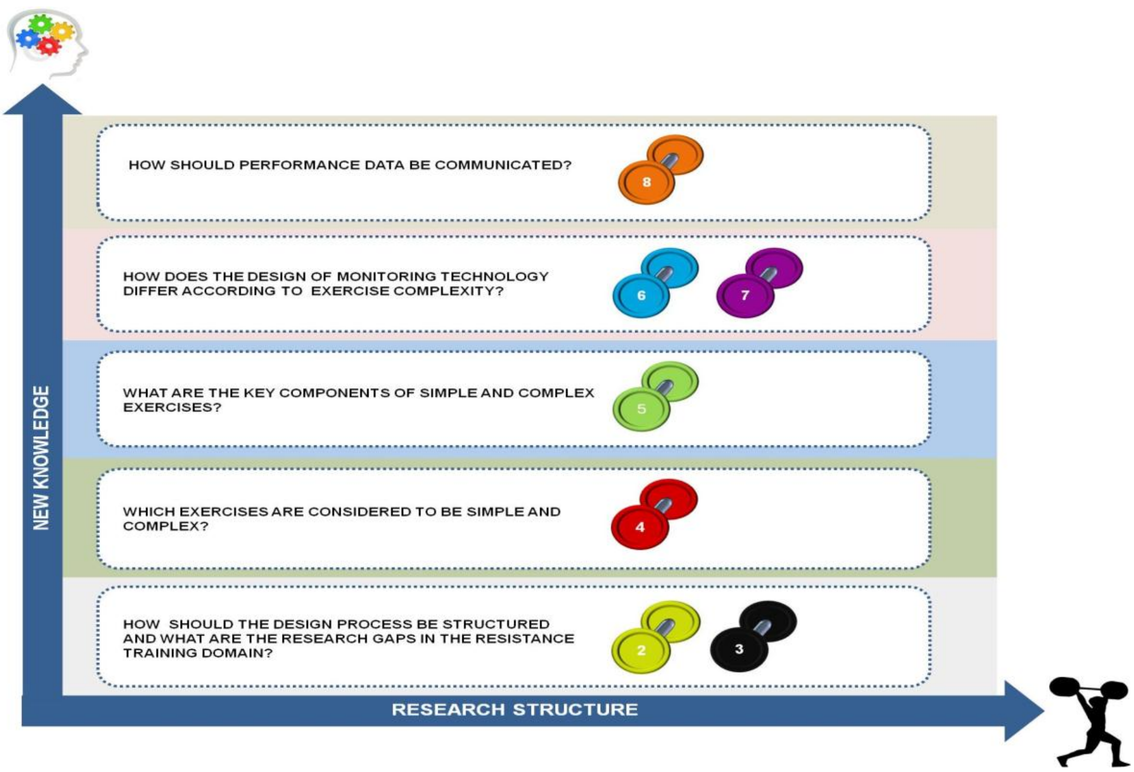


Figure 9.4 The core questions identified in Chapter 1 addressed in each Chapter to acquire new knowledge.

This structure was re-addressed in every chapter to demonstrate how new knowledge was acquired. A summary of the new knowledge is provided in Table 9.1. A summary of the new knowledge in relation to the core questions is presented in Figure 9.5.

Chapter	Research summary
2	• User centred design can be promoted by selecting themost iterative, flexible and systematic elements from numerous modelling techniques. • Combining the techniques is more useful than using each one is isolation.
3	• Bar rotation is a neglected area of research. • There is no distinction between simple and complex exercises using derived kinematic data.
4	• Re-iteration and filtering the user requirements according to user level has a significant effect, causing calorie feedback to change from the most important to least important performance monitoring variable. • Misuse of the acute training variables to structure a training program occurs more frequently in the endurance and hypertrophy zone. • The ability to perform more complex exercises is highly dependent upon the ability to perform a squat. There is a need to understand what the key components of simple and complex exercises to determine how monitoring and analysis can support the monitoring of both.
5	• High correlation exists between video, force platform and accelerometer acceleration profiles for simple exercises. • Correlation decreases as complexity increases. • Simple exercises do not inflict rotation of the bar and have linear trajectories. • Complex exercises inflict rotation on the bar and have non-linear trajectories. • A simple tri-axial accelerometer is not sufficient to accurately monitor complex exercises that inflict rotation. • A combination of technology is required to accurately monitor performance for complex exercises.
6	• A bar or waist mounted accelerometer can be used to monitor an increase or decrease in performance across sessions due to the high relative validity. • A bar or waist mounted accelerometer can be used to rank subject performance due to high relative validity. • Due to the high correlation between the waist node and video, whether jump performance can be monitored using a tri-axial accelerometer needs to be investigated. • A waist accelerometer could be used in a gym environment to provide squat jump analysis at a recreational level.
7	• A 2D transformation matrix is sufficient for monitoring in the resistance training domain. • Force platform and WIMU technology is required to fully characterise complex lifts using both bar and body kinematics. • Case study 3 results: a double plate force platform provides performance knowledge through the consideration of bilateral difference during a lift.
8	• The full combined methodology can be applied to the software and hardware domain. • The initial user derived requirements and testing requirements need to be combined to promote user centred design that matches the product capability. • Decomposition can be achieved using data flow modelling, domain classification and business process analysis. • Understanding the current and proposed data flow within the domain is fundamental to ensure that no data is left redundant. • The design methodology is flexible and can be applied to different sporting domains. • The partial level of the reference architecture distinguishes between the domain using requirements analysis.

Table 9.1 Summary of research conducted in Chapters 2-8.

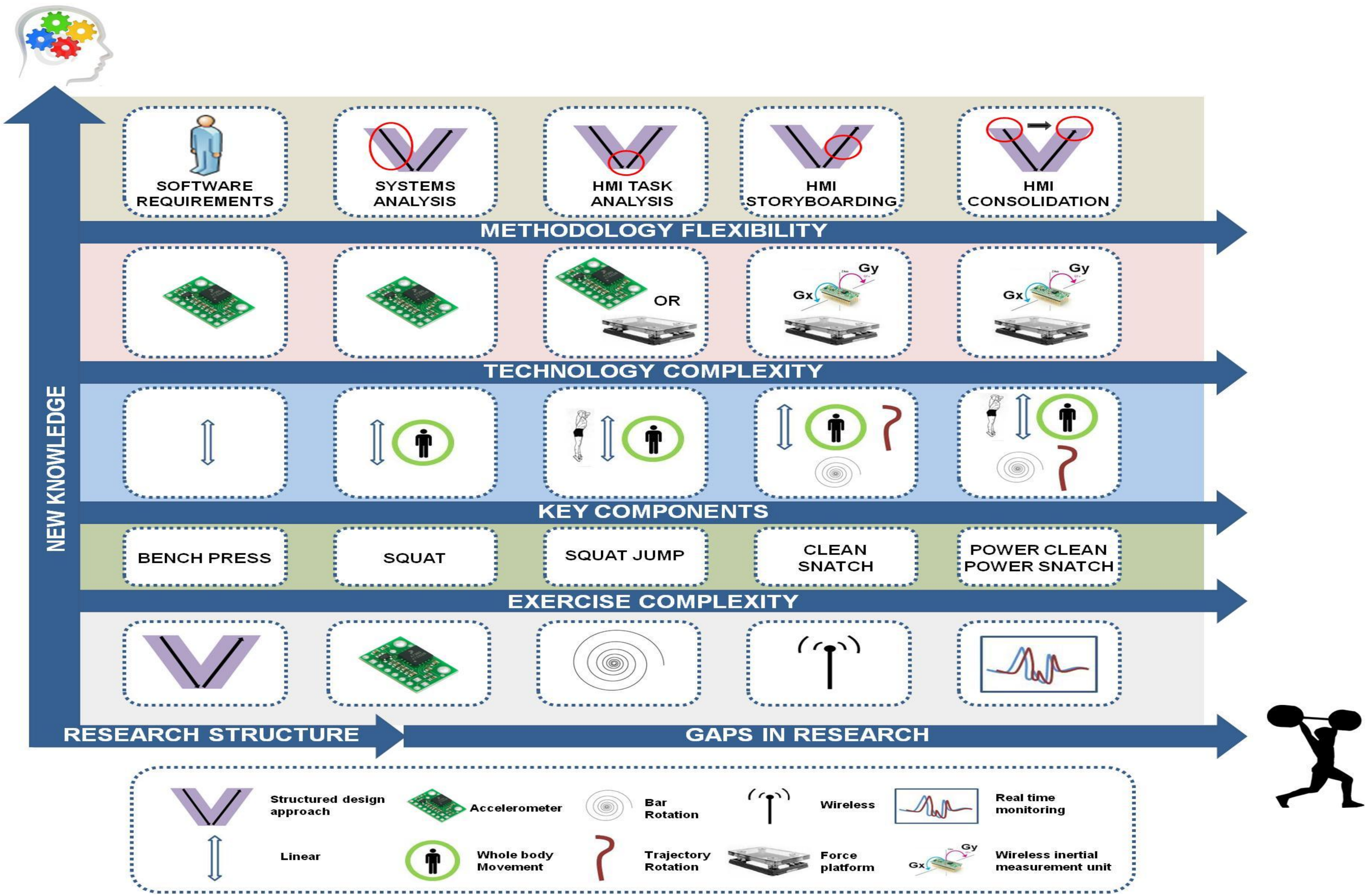


Figure 9.5 Summary of the new knowledge in relation to the core questions acquired as a result of the research.

Answering the core questions using the structure presented in Figure 9.5 identified the following:

- Combining the "vee" model decomposition and integration, CIMOSA framework, systems analysis data flow modelling and spiral process re-iteration provided a generic design methodology that is applicable to the sporting domain.
- Accelerometer research and consideration of bar rotation is limited.
- Wireless transmission to enable real time monitoring is not yet possible in the resistance training domain.
- A spectrum of exercise complexity was generated. The bench press and squat were considered to be the most simple and frequently used exercises in the gym environment.
- The most complex exercises were identified as the Olympic lifts.
- Complexity was determined by the number of key components required to execute the exercise.
- Simple exercises require linear, simultaneous bar and body movement and contact with the ground throughout.
- The most complex exercises inflict bar and trajectory rotation, involve whole body movement in which the bar moves independently of the body and include a dynamic jump.
- A simple tri-axial accelerometer is suitable for the analysis of simple, linear exercises.
- WIMU technology is required to monitor complex exercises that inflict rotation on the bar.
- A 2D matrix transformation is suitable for WIMU processing within the resistance training domain.
- WIMU and force platform technology maximises monitoring in the resistance training domain and enables bar and body kinematic data to be collected.
- The design methodology accommodated the development of software to ensure the collection, analysis and communication of data was achieved.

9.3 Future work

The research presented in this thesis was focused on the development of an elite based performance monitoring system using a user centred methodology. As several areas were addressed, future research should focus on further development within each area. The user centred design methodology was applied to the weightlifting and swimming domain, further research is required to investigate thoroughly the flexibility of the methodology.

The system designed to support performance analysis in the resistance training domain is in the early stages of testing. The research conducted in Chapter 7 only provided initial testing results using the WIMU and bayonet bar attachment, whilst the double plate force platform system requires further testing. Due to the research focus on the collection, analysis and communication of data, time constraints limited the analysis conducted using the combined system. Therefore, in order to validate the system, testing similar to that conducted in Chapters 6 and 7 is required. Future research should focus on understanding the full capability of the product to increase performance understanding. Functionality analysis indicated that monitoring of a simple, linear exercise could be achieved using a tri-axial accelerometer, whether a recreational product can be developed using accelerometer technology alone is an area to be investigated. The development of a waist mounted accelerometer should also be investigated as the results from Chapter 6 indicated that a simple tri-axial accelerometer could be used to monitor linear jump performance. The aim of the design methodology was to increase performance understanding, therefore, future testing of the WIMU and double plate force platform needs to be more focused upon sports specific testing to increase performance understanding rather than functionality analysis alone.

Future work should also consider the validation and re-iteration of the weightlifting software. The current system requires manual selection of each exercise rep in order to derive accurate kinematic data. Further analysis of a wider range of exercises using a wider population is required to establish whether a correlation algorithm can be used to automatically select reps. This would occur during the set up of the equipment, the user would perform the exercise to calibrate the system. This process is currently accommodated by the software but further research is required to determine whether this process is affected by changes in performance. Further signal processing research using the WIMU to distinguish key components of exercises would enhance further the performance knowledge acquired using the elite based monitoring system.

In Chapter 1, the development cycle within the sporting domain was discussed. The ability to increase performance understanding was identified as being dependent on sufficient research and development of monitoring technology to conduct sports specific testing sessions, from which performance data needed to be communicated. This cyclical approach is illustrated in Figure 9.6. The research documented in this project has targeted the first three elements of the cycle to provide a monitoring system to collect, analyse and communicate the performance related data. However, to achieve performance understanding, further testing and analysis is required using the developed technology for which numerous re-iterations of the same process is required. Therefore, more sports specific testing sessions need to be conducted using the developed system. Although thorough testing of the developed system has not been achieved, this research project has provided the functionality to support future testing to support performance monitoring in the resistance training domain. Furthermore, the design methodology provides a structure which can be applied to any sporting domain to develop both hardware and software to increase performance understanding at an elite and recreational level.

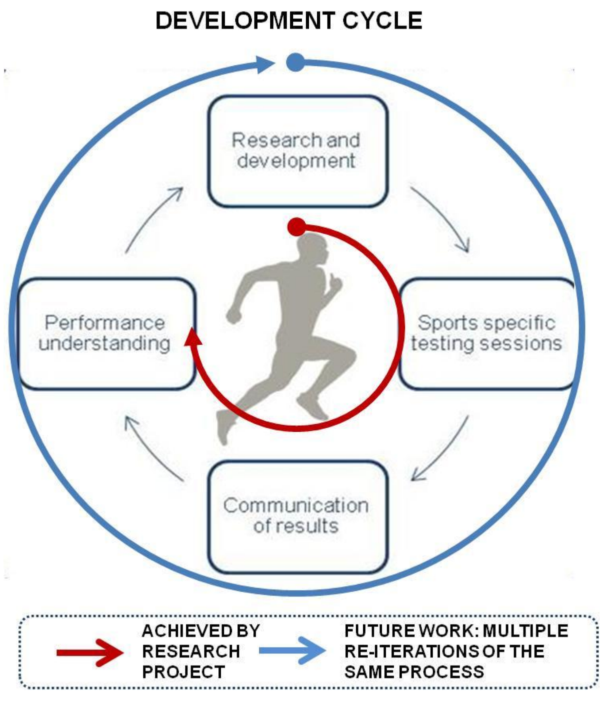


Figure 9.6 Illustration of the development cycle within the sporting domain required to increase performance understanding and identification of the need to repeat the cycle through future research.

10.0 References

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11.1 APPENDIX A: Pilot survey

MONITORING PERFORMANCE IN A GYM ENVIRONMENT

Section 1: Participant Information

Male ☐ Female ☐

Specialised sport(s)?

……………………………………………………………………………………………...................

Coach ☐ Elite ☐ Competitive ☐ Recreational ☐

How often do you visit the gym? (Please tick the relevant box)

Once a week ☐ Twice a week ☐ 3 times a week ☐ 4+ times a week ☐

Do you follow a structured resistance training program? Yes ☐ No ☐

Have you used any kind of performance monitoring technology before in a training or sports environment such as running watches or cycling power meters? If so please list below.

……………………………………………………………………………………………………

Section 2: Free weights and resistance machines

1. Please tick the upper and lower body exercises you **regularly** perform in the gym according to barbell, dumbbell and resistance machine use, if you perform the exercise using more than one method, please tick each one individually:

Exercise	Barbell	Dumbbell	Resistance machine (including cables)
Clean	☐	☐	☐
Snatch	☐	☐	☐
Overhead Press	☐	☐	☐
Deadlift	☐	☐	☐
Bench press	☐	☐	☐
Upright row	☐	☐	☐
Squat	☐	☐	☐
Jump squat	☐	☐	☐
Lunge	☐	☐	☐
Standing calf raise	☐	☐	☐
Bicep curl	☐	☐	☐
Bent over row	☐	☐	☐
Bent arm pullover	☐	☐	☐
Shoulder fly	☐	☐	☐
Frontal raise	☐	☐	☐
Shoulder press	☐	☐	☐
Chest fly	☐	☐	☐
Chest press	☐	☐	☐
Tricep extension	☐	☐	☐
Leg press	☐	☐	☐
Leg extension	☐	☐	☐
Leg curl	☐	☐	☐
Lat pulldown	☐	☐	☐
Hip ab/adductor	☐	☐	☐

Section 3: Monitoring your performance

2a. Please rank **the 3 variables** that you would most like to view during your training session. Rank preferences from 1 to 3, where 1 is the most important and 3 is the least important:

Quantifiable variable	View during training?
Peak power	☐
Average power	☐
Peak velocity	☐
Average velocity	☐
Peak force	☐
Average force	☐
Rate of force development	☐
Rate of power development	☐
Calories burned	☐

2b. Please give any reasons for selecting your **first** choice in the previous question?

3a. If the following 3 methods were available for measuring performance in the gym, please rank which of the following would be your preference from 1 to 3 (where 1 is most preferable, 3 is least preferable):

Task	Preference
A device worn on the wrist	☐
A device worn on the waist	☐
A device attached to the weight which is taken on and off between equipment changes (similar to a collar)	☐

3b. Please select **one** of the following reasons for your first choice in the previous question?:

Comfort ☐ Appearance ☐ Accuracy of data ☐

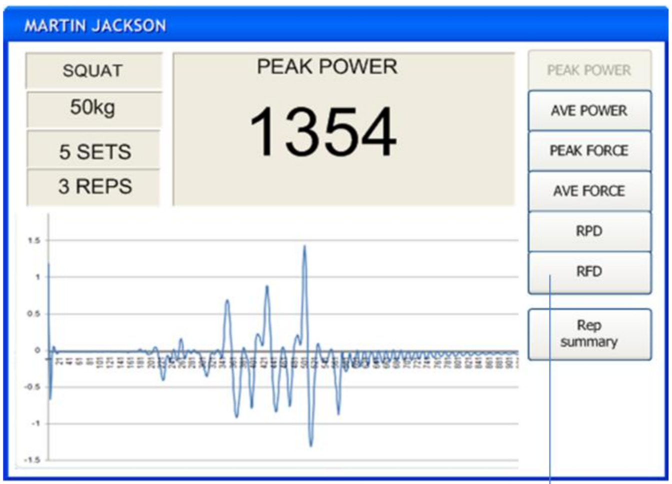
Section 4: Reviewing your performance

1. When would you prefer to see the measurements? (Please **tick one**)

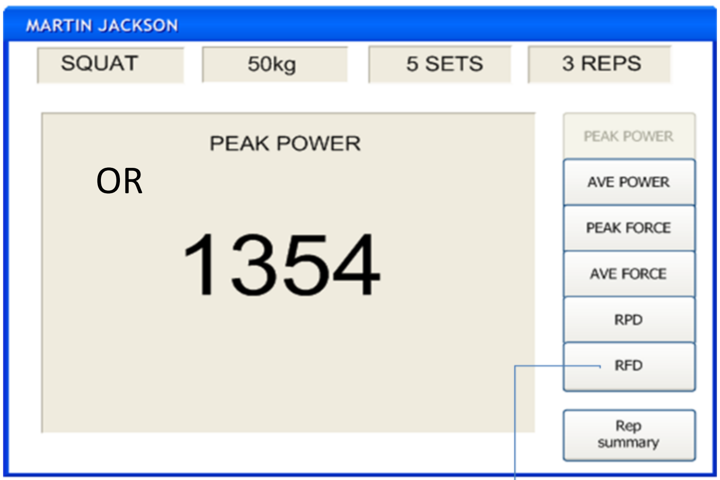
During a set ☐ After a set ☐ During & after a set ☐ After workout ☐

5a. Please circle which display you prefer between the pair given? (A or B)

A



B

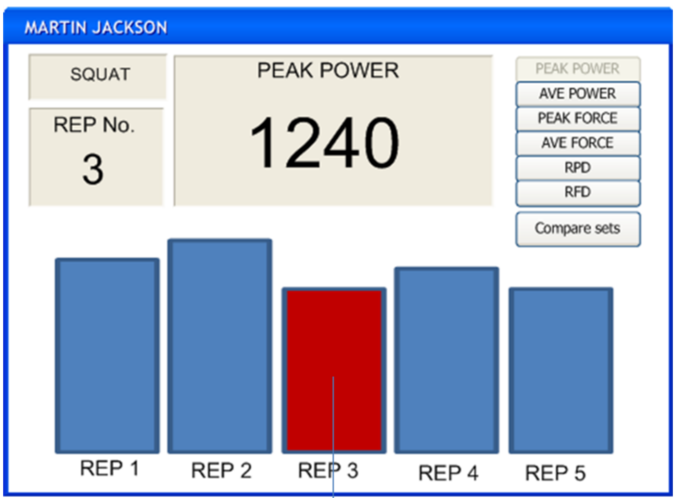


Select parameter you wish to view for set(s)

Select parameter you wish to view for set(s)

5b. Please circle which display you prefer between the pair given? (A or B)

A

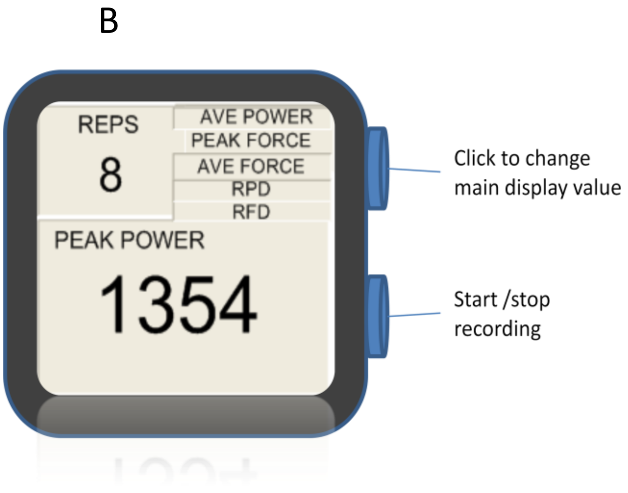


B

Select rep you wish to analyse

Select rep you wish to analyse

5c. Please circle which display you prefer between the pair given? (A or B)



6. Can you please detail any reasons for your choices to question 5 (parts a, b and c)?

Please ensure you have completed all questions on the front and back of each page.

Thankyou for completing the questionnaire, all information remains confidential and is used for research purposes only.

11.2 APPENDIX B: Calibration

The data sampled from the WIMU requires manipulation in order to derive useful information. An example of one sample is presented in Figure 11.1. In this example the WIMU was not moving and the X axis accelerometer was experiencing 1G. The equation for the line presented in Figure 11.1 was used to relate the raw values to acceleration in meters per seconds squared. The "R2" term indicated that there was a linear trend between the acceleration and raw acceleration values ensuring that the equation describing the relationship could be used with confidence. Each accelerometer was calibrated to increase the accuracy of the converted data. Gyroscope calibration was achieved by rotating the device under known conditions. The relationship between the known speeds and raw gyroscope data was analysed and an equation derived to integrate the values. The gyroscope data was converted to radians per second.

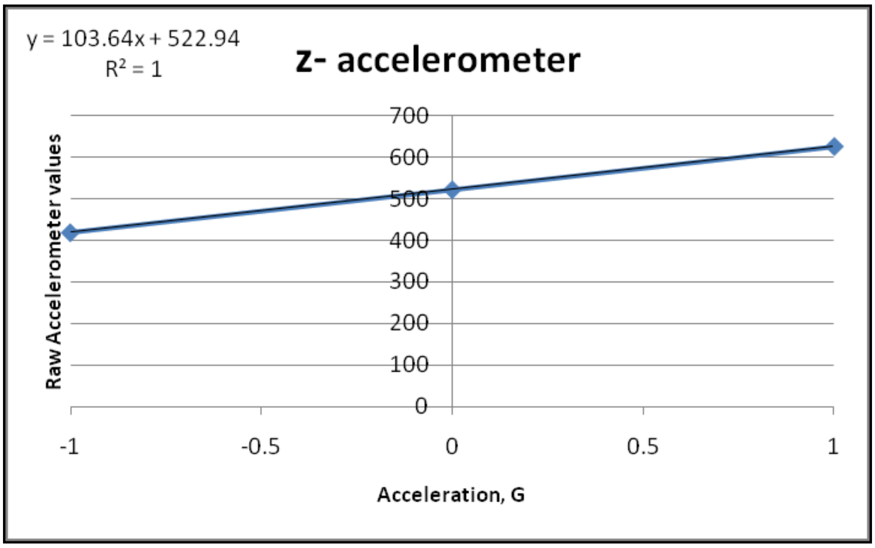


Figure 11.1 Linear trend between raw and converted accelerometer output.

11.2.1 Accelerometer Calibration

The WIMU was clamped and aligned using a dial gauge and a set square. The calibration of the z axis is demonstrated in Figure 11.2. To ensure the WIMU was parallel to the surface a dial gauge in a fixed position was used to measure the height in multiple areas on the board. The WIMU was adjusted in the vice until the overall difference was within 0.2mm. This same method was employed when reading -1G in which the WIMU was rotated 180 degrees.

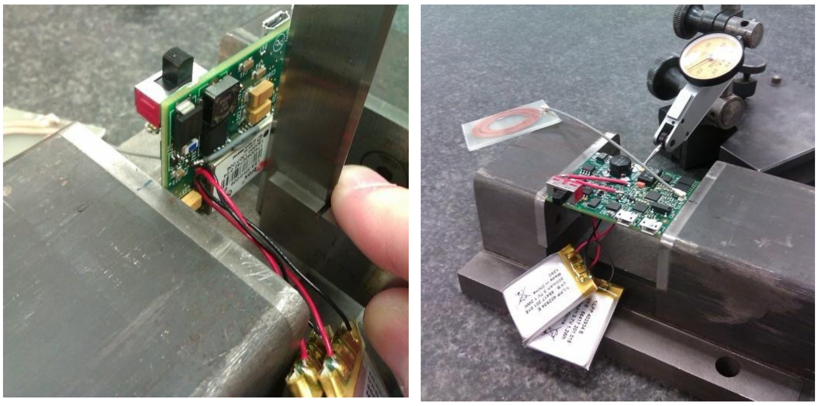


Figure 11.2 Aligning WIMU in calibration box with set-square

Each accelerometer was rotated in 3 positions to read 1, 0 and -1G. In each position three readings were taken, switching the accelerometer off in between each one. A test was conducted to compare the accuracy of the gyroscope rig and the accelerometer calibration method. The results presented in Table 11.1 indicate that there was a difference between the two methods with a maximum average error of 0.08% (when reading 1G is equivalent to 7.85x10-3ms^2). Any error in theses acceleration values would be propagated through its integration to velocity and position.

Axes	Amount of G's	Value in Box	Value flat	% error
X	1	625.1483	625.4002	0.04
	0	523.9708	524.1029	0.03
	-1	422.9725	422.9821	0.002
Y	1	623.5208	623.5487	0.004
	0	518.3814	518.598	0.04
	-1	413.3831	413.0427	0.08
Z	1	615.6542	615.7032	0.008
	0	513.3135	513.1008	0.04
	-1	410.7877	410.7528	0.009

Table 11.1 Percentage error in accelerometer output between an enclosed and WIMU

11.2.2 Gyroscope Calibration

In order to rotate the WIMU at known angular speeds a rig was built to hold the WIMU securely in alignment with the centre of rotation. The rig was designed to hold the WIMU parallel to the outer surfaces whilst being placed into a lathe with a four-jaw chuck. A small drill bit was used in the lathe to accurately be align the WIMU against the centre of the lathe's rotation. The adjustment in the alignment came from the utilisation of the four jaws of the chuck.

To calibrate the WIMU and investigate the feasibility of the method the first batch of WIMUs calibrated were spun at 25, 40, 55 and 80 revs per minute (RPM). Each gyroscope was spun at each of these speeds three times for 10 seconds. The WIMU was aligned by locating the centre of the gyroscope with the drill. To test the need for such alignment, the WIMUs were also spun without this alignment whilst still retaining the gyroscopes axis parallel to that of the lathes centre of rotation. It was important that the lathe was not assumed to be rotating at exactly its specified angular speed. The two accelerometers sat perpendicular to the gyroscope under calibration experienced peak acceleration when their axis was aligned vertically both positively and negatively. An example of the accelerometer output is illustrated in Figure 11.3.

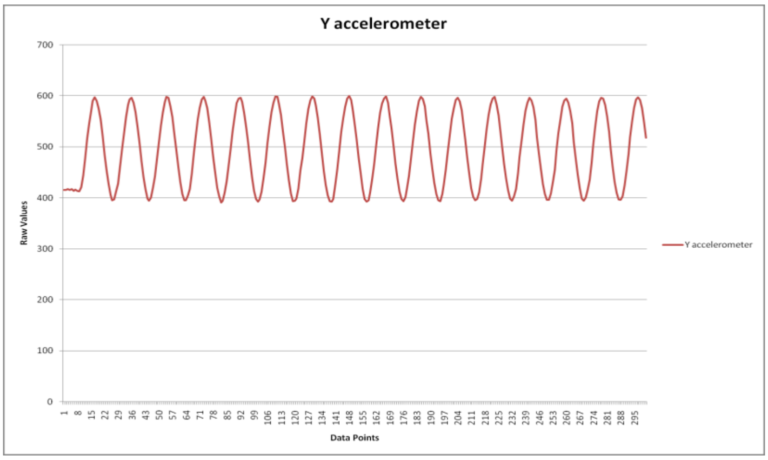


Figure 11.3 Accelerometer output during calibration testing

The distance between the peaks represent the time elapsed between each rotation, allowing the lathe speed to be calculated. The results indicate that gyroscope alignment does affect the output, therefore ensuring gyroscope alignment with the centre of rotation is required for accurate calibration results. The calibration results presented in Table 11.2 indicate that this method was feasible for gyroscope calibration. For increased accuracy a purpose built rig which incorporates the functionality of the lathe i.e. through an electric motor should be designed.

Gyroscope	On centre calibration equation	Off centre calibration equation
X	Y = -16.626x + 493.92	Y=-16.62x + 494.92
Y	Y = 17.26x + 540.43	Y=17.429+ 540.01
Z	Gyroscope Not Functional	

*y= raw value, x=rotational velocity, rads/s

Table 11.2 Accelerometer readings during gyroscope calibration

11.2.3 Gyroscope summary

1. Position WIMU in the calibration box aligning as best as possible, use small set square.

2. Using a lathe with a four-jaw chuck set calibration box with WIMU inside flat against chuck and align with jaws. Align gyroscope component through box's window to a small drill bit in the lathe.

3. Spin WIMU at a minimum of 4 angular speeds, such as 25, 40, 55 and 80rpm for approximately 10 seconds.

4. Process data by first finding actual RPM of the lathe using accelerometer values. Relate raw gyroscopes values with lathe speed via a scatter graph, plot trend line and calculate equation of the line.

5. Input these individual equations for each gyroscope into software.

6. WIMU's gyroscopes are now calibrated and can be used to capture actual data.

11.2.4 Accelerometer summary

1. Clamp the WIMU to a vice on a flat surface.

2. Ensure WIMU is parallel or perpendicular to surface with the use of dial gauges and set-squares.

3. Record data for the WIMU twice for at least 10 seconds in each position.

4. Process data one accelerometer at a time. Relate raw acceleration values with known values, 1,0,-1 G.

5. Plot trend line and calculate equation of the line. If trend does not appear linear more testing is necessary to determine accelerometer functionality.

6. Input these individual equations for each accelerometer into software.

7. WIMU's accelerometers are now calibrated and can be used to capture actual data.

11.3 APPENDIX C: Bayonet design

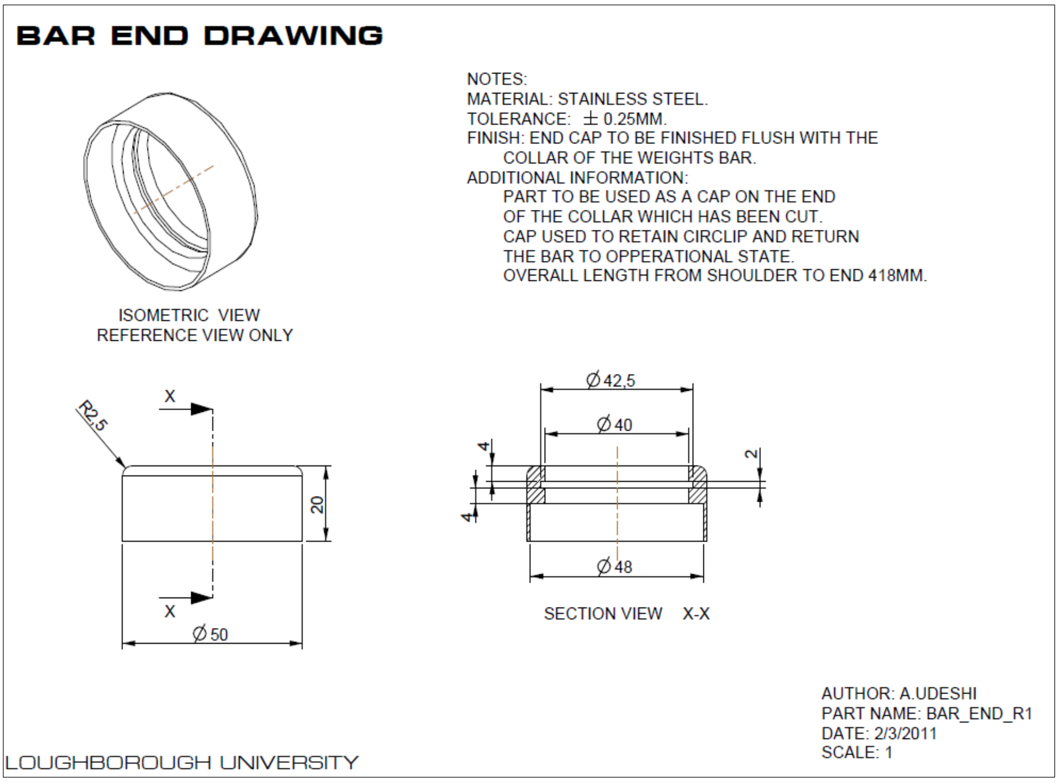


Figure 11.4 Bayonet bar end engineering design

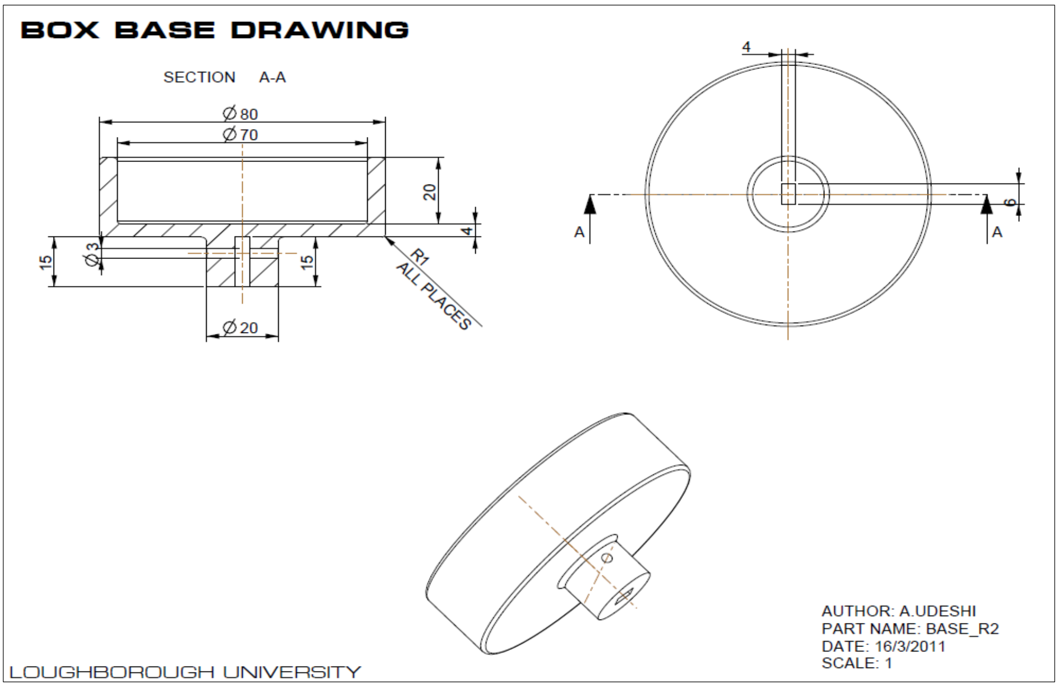


Figure 11.5 Bayonet box base engineering design

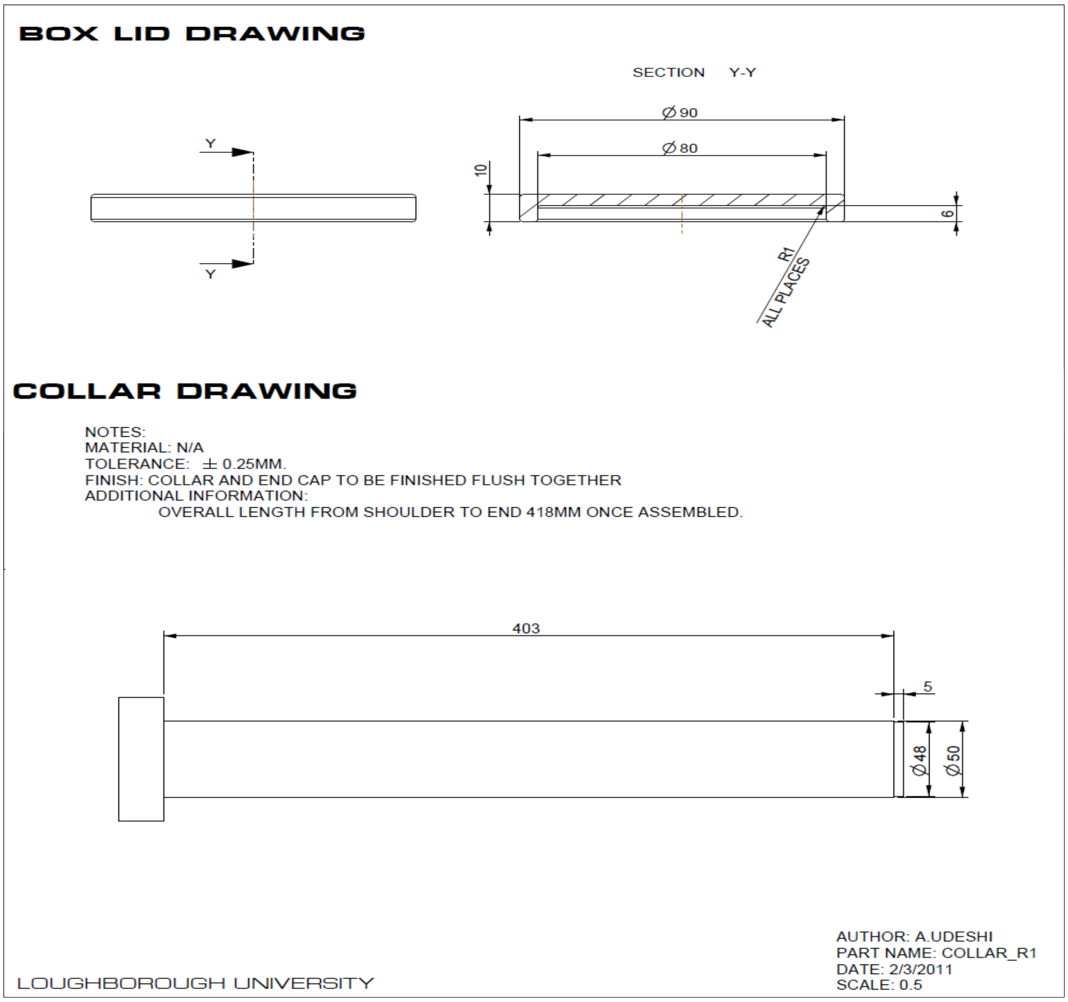


Figure 11.6 Bayonet box lid engineering design

11.4 APPENDIX D: Force platform design and PDS

Ixthus Force Plate (3axis) bill of parts		
COMPONENT	**No. off**	**Drwg No.**
Main components		
Top Plate (25mm) [left]	1	003
Top Plate (25mm) [right]	1	005
Bottom Plate (20mm) [left]	1	004
Bottom Plate (20mm) [right]	1	006
Small access caps	10	012
Large access caps	4	013
Steel transducer discs A (2mm)	8	007
Steel transducer discs B (2mm)	8	008
lateral transducer block A	4	009
lateral transducer block B	4	010
Steel transducer coupling shaft	4	011
Bolts, screws etc		
Floor expansion bolts (M10)	24	-
Levelling grub screws (M10)	12	-
Transducer locating screws (M6)	24	-
Transducer disc locating grub screws (M4)	48	-
Lifting hookeye bolts (M10)	10	-
Lifting bolt caps (M10)	20	-
Large cap locating screws (M5)	12	-
Transducer block bolts (M4)	16	-
M10 Silver Steel Pins	8	-
Transducer components		
Ixthus Loadcell	8	RLC C3
Tension/Comp Loadcell	4	8417 6001
In-Line Amplifier	12	9235
Tools		
Cap lock tool	1	-

Table 11.3 Three axis Ixthus force platform bill of parts

	Stock Kistler	Designed Kistler	Ixthis (3 axis)	Ixthus (1 axis)
Functionality	3-axis	3-axis	3-axis	1-axis
Plate Cost	-	£1,180	£1,180	£1,180
Transducer Cost	-	£26,000	£8,240	£5,240
A/D Cost	-	£2,000	£2,000	£1,000
Manufacturing Cost	-	£2,500	£3,000	£3,000
Total Cost	£50,000	£31,680	£14,420	£10,420
% Saving	-	37%	71%	79%

Table 11.4 Force platform cost comparison

1 Performance

1.1 The device should measure the vertical (Z) and lateral (X and Y) components of the ground reaction force exerted by a user on the plates.

1.2 The vertical (Z) component measured by each plate must have a range of 0-10kN

1.3 The device should give accurate and repeatable results when installed onto a concrete surface.

1.4 Levelling screws and ground fixing bolts on the bottom plate should be accessible while the top plate is installed.

1.5 The device should be fastened securely to the ground with no possibility of being ripped up by the use of a fixed isometric bar.

1.6 The top plate surface should be smooth wrt not having exposed or unfilled holes

1.7 The device should have adequate holes available in the bottom plate for allowing an isometric bar to be retrospectively fitted.

1.8 The top plate of the force plate must have a maximum deflection under loading of 2mm across its area to ensure a load normal to the force plate is transmitted accurately through the transducers.

2 Environment

2.1 Device operational inside within a gym environment

2.2 Device must be water resistant (athletes sweat)

3 Life in Service

3.1 Should withstand an operational period of 8 hours uninterrupted use per day for a period of 5 years.

4 Target Costs

4.1 The product has an end use maximum cost for a pair of force plates of £15000.

4.2 The cost of manufacture of a pair of force plates should be a maximum of £ 3000

5 Maintenance

5.1 Ground fixings and levelling screws must be accessible when the top plate is installed.

5.2 Other than the above and software updates and calibration, the device should be maintenance free.

6 Size Restrictions

6.1 The depth of the assembled installed plates must not exceed 65mm

6.2 The area of each top plate (working area) should be 900x500mm to fit the location, within a tolerance of +/-10mm.

6.3 The maximum footprint of the force plate pair is 1000x800mm.

7 Aesthetics

7.1 Top plate top surface should be brushed to give an even finish.

7.2 The ‘Loughborough University’ logo is to be embedded into the top plate top surface

7.3 The ‘SmartWeights’ logo is to be embedded into the top plate surface.

8 Ergonomics

8.1 Top plate top surface should be brushed to give an even but rough finish for grip.

9 Lead Time

9.1 Force plates to be machined by mid June 2011.

10 Component

10.1 Sensors

10.1.1 Must use Vishaye RLC Ring Torsion Load Cell type C3 (for vertical force component)

10.1.2 Must use Burster Subminature Load Cell type 8417-6001 (for lateral force components)

10.1.3 Must use Burster In-line Amplifier type 9235-E