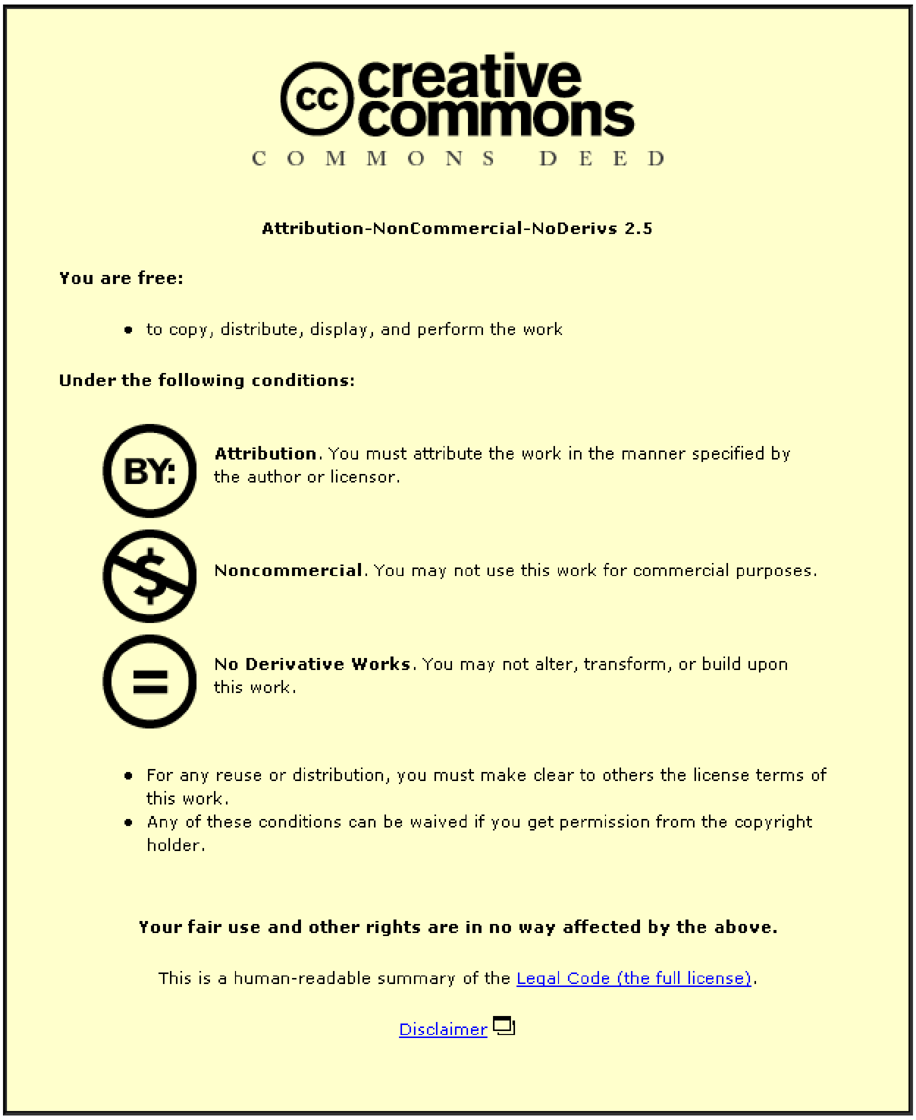
Research, design and testing of a multi-function modular exercise system



RESEARCH, DESIGN AND TESTING
OF A
MULTI-FUNCTION MODULAR EXERCISE SYSTEM

By

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SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY
AT
LOUGHBOROUGH UNIVERSITY
LOUGHBOROUGH, UK
JUNE 2007

Abstract

The aim of this research was to develop a novel multi-function exercise system for use in a broad range of applications. Market research indicates that the demand for aerobic and anaerobic exercise devices will continue to grow with the introduction of government physical activity guidelines and increased social pressure regarding health related issues. A detailed investigation of the basic exercise science fundamentals and training methodologies was conducted in order to develop a system which would provide efficient and effective training related stimuli for improving fitness. The generation, storage and utilisation of actual and virtual load and velocity profiles for use in the development of original training modes was identified as an important area of the research.

The proposed solution utilises an electromechanical programmable motion control system which provides all of the necessary exercise modalities defined in the system specification. This system combines existing industrial servo drive technology with proprietary software and database facilities to provide a step change in functionality, ease of use and safety for all users. Development of these hardware and software elements was supported by the creation of a series of system models at the initial stages of the research using the computer integrated manufacturing open systems architecture (CIMOSA) modelling approach. These diagrams were an invaluable resource during the concept generation and refinement processes and have clearly demonstrated the cross-discipline applications of such formalised modelling techniques.

Validation and reliability data collected during prototype testing indicated that the exercise motion generation capabilities and performance measurement facilities were comparable to existing isokinetic dynamometer equipment. Additional subject testing produced results with peak output values and parameter trends which correlated closely to those determined during clinical and academic research. These experimental results suggest that the modular exercise system could be a valuable tool for the collection of research data to be used in support of current and future training theories.

Keywords: Fitness equipment, resistance exercise, CIMOSA, enterprise modelling, Variokinetic exercise, strength training, aerobic exercise.

Acknowledgements

This project has shown me yet again what can be achieved with perseverance and hard work. However, such an achievement could not be realised without a supportive network of friends, family and colleagues. First and foremost I would like to thank my supervisor and mentor Dr. Andrew West for the guidance, experience and knowledge that he has provided throughout the period of this work. I would also like to personally thank Stuart Mcleod for his input and assistance with the software design and development aspects of this study, and for the general encouragement that he expressed during our time working together.

I am extremely grateful to all of my colleagues in the MSI and Sports Technology Research Groups at Loughborough University who have supported and aided me in my studies. Special thanks must be given to Sports Technology technicians Steve Carr and Andrew Hallam who provided invaluable knowledge and advice during the production and assembly of the exercise system. Without their unquestionable manufacturing skills and patience, the prototype system would still be no more than a series of drawings.

Finally I would like to thank my family and friends, especially my parents and my girlfriend for showing the kind of unwavering support and belief that only those that are truly closest to you can provide.

Publications arising from this work

West, A. A., Smith J. D., Monfared, R. P. & Harrison, R. (Accepted). Formalised requirements documentation of a novel exercise system using enterprise modelling concepts, *Asia-Pacific Congress on Sports Technology,* Singapore.

Smith, J. D., West, A. A., Monfared, R. P. & Harrison, R. (Under review). Application of enterprise modelling techniques in the design and development of novel exercise equipment. *Proceedings of the I MECH E Part B Journal of Engineering Manufacture.*

Smith, J. D. & West, A. A. (Under review). Modular rehabilitation exercise system with enhanced functionality and safety. *Journal of Sports Sciences.*

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Introduction

Exercise participation has become an important social issue in modern society that is being driven by Government health strategies and public health promotions aimed at reducing the incidence of obesity, heart disease, strokes, osteoporosis and non-insulin diabetes through preventative methods (Department of Health, 2004). The integration of additional physical activity into the everyday routines of all age groups within the general population is encouraged to lessen the impact of increasingly sedentary lifestyles. The prescription of specialist exercises is also an important element in rehabilitation and physiotherapy programs from the impairments listed and additional neuro-physiological and physical afflictions. In contrast to the controlled movements used in the medical domain, dynamic exercise concepts are widely utilised in the training and conditioning of competitive and elite athletes in order to improve overall performance. Although the precise requirements of these disciplines differ, the resultant effect of expansion in these areas is driving research to improve participation and motivational aspects, enhance equipment design and develop efficient and effective training systems.

The aim of this Ph. D. is to develop a novel training / rehabilitation system which will integrate easy to use human interfaces, new and existing training modes and advanced safety features in a single modular unit. The primary research questions to be addressed during this study can be summarised as follows:

> **Research question 1 -** What training methods and exercise approaches exist for improving general health and sporting performance?

Research question 2 - What are the influential factors of exercise equipment design in determining user participation and motivation?

Research question 3 - How can the operation of exercise equipment be improved by utilising formalised systems modelling concepts?

Research question 4 - How can existing technologies be utilised in the creation of an advanced training system which demonstrates the appropriate exercise modes established in research question 1 and operational requirements from research question 3?

Research question 5 - How can the design and implementation of current exercise interfaces be enhanced to improve usability?

Research question 6 - What performance capabilities can be achieved using the technologies identified in research question 4?

The major technical objectives identified to support the research questions can be defined as follows:

(i) Review of exercise fundamentals and training methodologies with a view to identifying and implementing state of the art approaches.

(ii) Critical evaluation of existing exercise equipment leading to the creation of a focussed specification document.

(iii) Identification and implementation of a suitable systems modelling technique.

(iv) Design and development of a proof of concept multi-function modular exercise system demonstrator.

(v) Produce a user friendly, reconfigurable and scaleable user interface for system configuration and performance monitoring.

Chapter 1

Literature review –
Exercise fundamentals and training methodologies

1.0 Introduction

The aim of this research was to develop a novel exercise system which would provide advanced levels of functionality. In order to understand fully the operational requirements of the system and the human reaction to applied training stimuli from such equipment, a comprehensive review of exercise literature was undertaken. The influential factors and prior knowledge that was considered as integral to the inception of the development process are illustrated in Figure 1.1.

As developed society has shifted inextricably towards an increasingly sedentary life style, the concept of exercising as a leisure activity has become an important determinant in the overall health of the population. The decrease in the nominal condition of an average citizen can be attributed to a general reduction in physical activity, dependence on assistive technologies and excessive calorific intake. In order to lessen the impact of this trend, the general public is being encouraged to participate in additional exercise to help maintain fitness levels and well being.

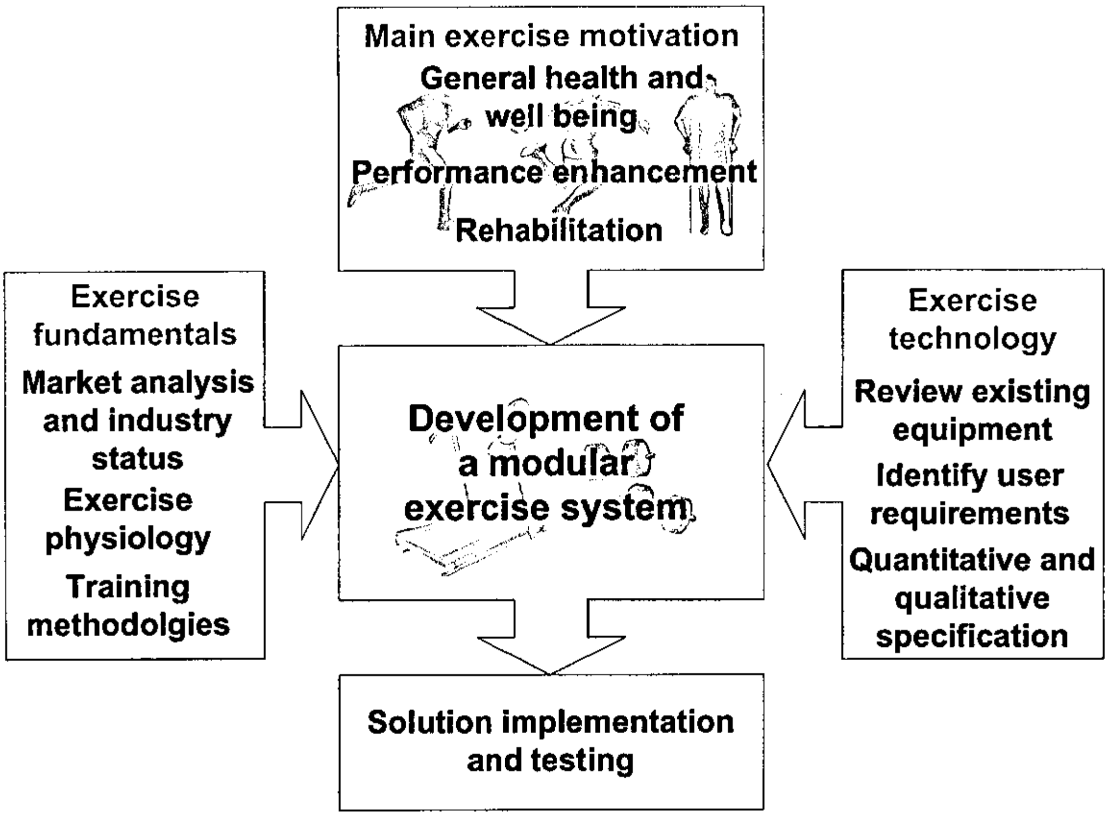


Figure 1.1: User demographics and background information required for the development of a novel exercise system.

Although the mainstream exercise focus has been approached from a healthcare perspective, physical exertion is also used in medical rehabilitation and for athlete performance enhancement. Modern recovery procedures for patients who have suffered from physical injuries and neuro-physiological impairment will involve some form of physical therapy to assist in the recovery of muscle activity and control. Specific exercise characteristics associated with these remedial activities include low load, slow speeds and tightly controlled range of motion. At the other end of the fitness spectrum are elite athletes. These individuals utilise exercise to artificially increase performance and stamina for improved results during competition. The training programs proscribed by an athlete and / or coaching staff are varied although the overall intensity and volume is likely to be relatively high when compared to casual gym users. Emphasis is placed on the development of sports specific attributes such as strength, power or endurance.

As shown in Figure 1.1, it is important to understand the fundamentals of exercise science and existing technology before embarking upon the production of a new system. Knowledge of the market conditions and influential factors should provide an insight into equipment usage and motivation aspects. A review of exercise physiology and training methodologies was also conducted to identify the primary exercise modes for inclusion in the proposed system. Additional information regarding the capabilities and shortcomings of existing technologies is discussed in Chapter 2 together with the general operational requirements.

1.1 Exercise market and influential factors

The exercise market has experienced rapid and continual growth in recent years. Part of this expansion can be attributed to an increased awareness in the general population regarding health related issues. The proliferation of educational material relating to the dangers of obesity and associated conditions due to inactivity is being primarily driven by national governments. For instance, a report published in the UK by the chief medical officer (Department of Health, 2004) identified that the direct and indirect costs incurred by the state through personnel inactivity is approximately £8.5 billion, with at least one quarter of the adult population now considered to be clinically obese. This report outlines the benefits of exercise and recommended activity levels for people at all stages of life. The recommendations are generally focused upon the inclusion of some form of aerobic exercise in everyday routines (e.g. walking, cycling or swimming). However, it is acknowledge that participation in anaerobic exercise (e.g. exercising with free weights or weights machines) can help to reduce the onset of musculoskeletal conditions, such as osteoporosis, and maintain a healthy physical condition.

The result of these government health strategies combined with an increased social pressure to enhance appearance and health, has lead to an increase in the purchase of exercise equipment and fitness related services. The exercise market can be segmented into three main areas: home fitness, commercial facilities and specialist institutions. The Mintel International Group (Mintel International Group Ltd, 2003) produced a detailed study of the UK in-home fitness market, worth £230 million at the time of the study, which provided some useful information in the development of the training system. Data regarding the frequency of in-home exercising shows that the majority of the people covered by the survey exercise at least once a week. However, the study also identified a high number of users (31%) who had at one stage exercised at home but had subsequently failed to continue this regime in the 6 months prior to the study. This trend represents the difficulty that many consumers have in maintaining their interest and commitment to extended exercise programs.

The findings indicated that more than half of all adults surveyed have some form of in-home fitness equipment in their household. Research suggests that cost is a major influence on purchasing decisions with a trend towards lower value items due to long term usage concerns. The information also indicates that sales are influenced further by advertising and fashion, which suggests little understanding or concern for the actual exercise benefits offered by the equipment available.

The impact of technology on the exercise market and its increasingly important role in in-home fitness equipment where new developments are driving sales are discussed in the report. Trends set by commercial market leaders in response to new consumer demands are focused on the development of "cross-trainers" that exercise several parts of the body simultaneously in order to reduce training time. Focus is also being placed upon the provision of new methods for improving the presentation of feedback information and analysis results regarding user performance. Reference has been made to the inclusion of entertainment features within exercise systems to allow the user to play games, watch films or listen to music with a future vision of training in a completely virtual environment.

Allegra Strategies published a report (FIA information series, 2003), based on 4,065 interviews with UK health and fitness club members, detailing aspects of the UK health and fitness market. The report found that 61.4% of the interviewees were not a member of a fitness club 6 months prior to joining their current centre. The data suggests that there is still strong scope for growth within this market. A small percentage (i.e. 7.9%) of people also stated that better equipment would encourage them to visit their preferred club more often. The results received when the test population where questioned about the facilities they most frequently used are illustrated in Table 1.1. The relatively high popularity of strength machines should be noted, but also the significant difference in usage of strength machines when compared to free weights for females.

Gender		**Facility category**	
	Cardiovascular	Strength machine	Free weights
Male	84.70%	70.40%	57.80%
Female	83.50%	59.60%	32.20%

Table 1.1: Results from the UK health and fitness club market study for the investigation of facility usage. Reproduced from FIA information series (2003).

The health and fitness omnibus survey (Leisure-net solutions, 2004) was conducted to provide an overview of the nation's attitudes towards exercise. The results from this research indicated that a high proportion of individuals do not do as much physical exercise as they would like to, with 39% of people undertaking no moderate level physical activities in a 3 month period prior to the study. When questioned, non gym users stated that the most important factor in choosing a training facility would be a good range of equipment and friendly, qualified staff. Feedback from staff and clear performance monitoring was found to be the key factors for maintaining participation. The main motivation for joining / attending a gym facility was found to be a desire to improve general fitness although reducing weight and altering body shape were also deemed important.

The specialist rehabilitation market is relatively small compared to the commercial and home fitness domains. Rehabilitation equipment is generally found in medical / academic institutions or dedicated training facilities. A Mintel report (Mintel International Group Ltd, 2007) on medical equipment estimated the market for therapeutic medical equipment is worth £178.8 million although a declining trend in value (5% decrease in the year prior to the study) has been identified in the study. A diverse range of rehabilitation devices are available although each item generally has a highly specific purpose and single dedicated function. With a limited market such as this, many manufactures are looking to diversify the technology into mainstream applications. In this environment it is essential that the practitioner is able to control closely the exercise and accurately monitor the progress of the patient. Therefore, the exercise systems developed for these applications tend to utilise relatively advanced technologies, when compared to traditional equipment, and subsequently have a considerably high unit purchase cost which is typically in the region of £10,000 - £50,000.

Following the market review, there appeared to be an opportunity to develop a broad range, modular exercise system that could be used effectively in the exercise environments identified. A summary of the primary requirements for the three exercise domains is illustrated in Figure 1.2. By incorporating the control and monitoring facilities required for rehabilitation equipment into an easy to use, cost effective and safe package it could be possible to produce a system which would provide a suitable platform for conducting both aerobic and anaerobic exercise.

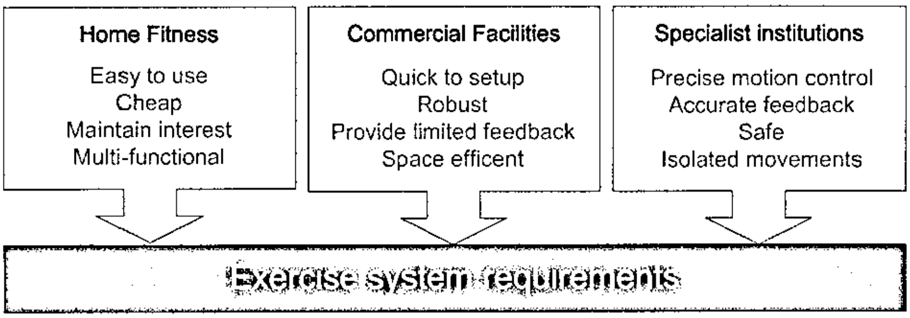


Figure 1.2: Generalised requirements for the main exercise markets identified.

1.2 Exercise science fundamentals

Human movement is the result of a complex interaction between anatomical, physiological and biomechanical systems. In order to develop any form of exercise device it is essential to understand the principles behind human force generation to ensure that both design and operational components of the system support the underlying biological requirements and capabilities. The origin of human output force is widely accepted as consisting of two core mechanisms: muscular actions and neurological drivers. A decomposition of the theory behind muscular force production is illustrated in Figure 1.3. Each of the elements identified in the diagram is discussed in the following sections.

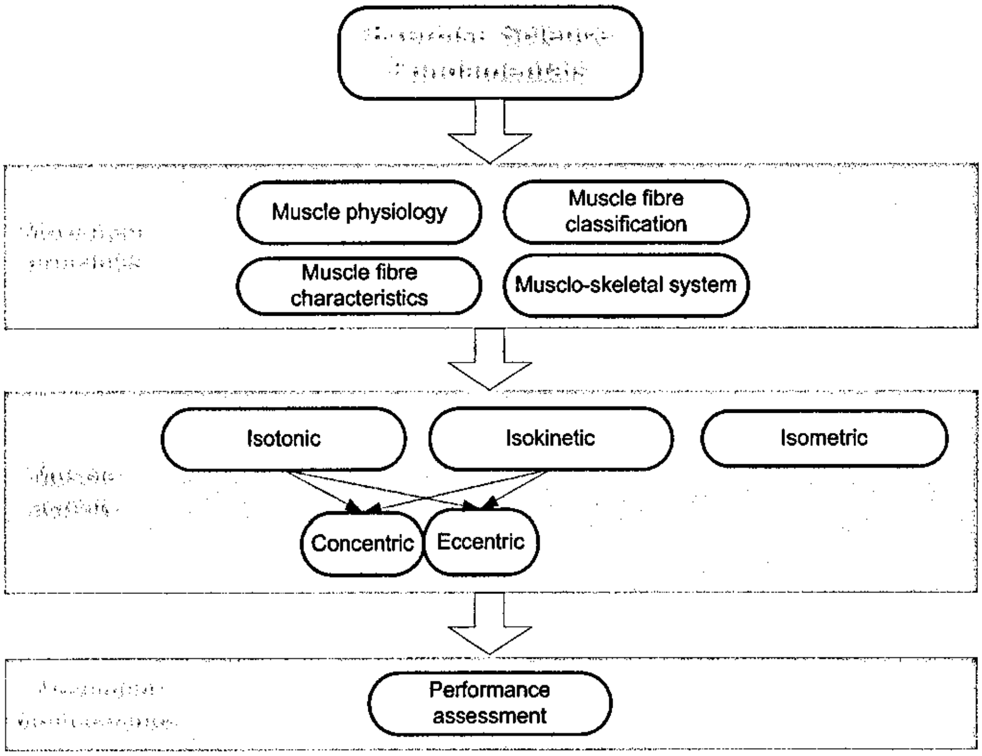


Figure 1.3: Essential aspects of exercise science fundamentals for developing a training system.

1.2.1 Muscle physiology

Human muscle is composed of bundled muscle fibres which produce a force in a planar direction. Each muscle fibre consists of a large number of myofibrils that in turn are constructed of a linear series of sarcomeres. Sarcomeres are the fundamental contractile units in the muscle and consist of a two contractile proteins: thin filaments known as actin and thick filaments known as myosin (Jones & Round, 1990). The structural composition of the skeletal muscle is shown in Figure 1.4.

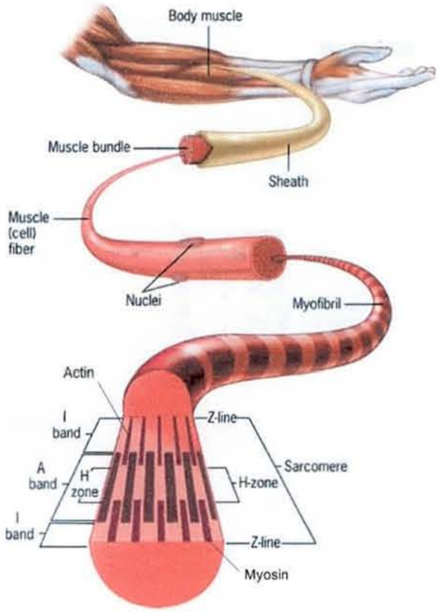


Figure 1.4: Schematic of the structural composition of skeletal muscle. Reproduced from Karp (2001).

Muscle fibres contract through a shortening action of the myofibrils. This mechanism, known as the sliding filament theory (Billeter & Hoppeler, 1992), describes the process of actin protein moving relative to myosin protein. The biological basis of the sliding filament theory is well documented and is principally based upon a process known as the cross bridge cycle (Greeves & Holmes, 1999). This chemical process is described in four stages during which the myosin uncouples from the actin, reattaches, creates relative movement and detaches. This continues in a cyclic manner until neurological and chemical signals indicate that the desired contraction is complete.

1.2.2 Muscle fibre classification

The biological basis for movement of skeletal muscles is common for all muscle groups regardless of anatomical position. However, skeletal muscle fibres can be categorised into three distinct types (Billeter & Hoppeler, 1992), with the exact proportion of each fibre type within the muscle dependent upon the typical operating conditions. The three types of skeletal muscle documented are:

(i). Type I Fibres. These fibres, commonly called "slow twitch" have a slow contraction velocity but exhibit excellent fatigue resistance characteristics. Such fibres are found in large numbers in the postural muscles of the neck and heart.

(ii). Type II A Fibres. These fibres, known as fast twitch provide fast contraction velocities and offer greater resistance to fatigue then type II X fibres. The quantity of type II A fibres found in human muscle is relatively small compared to the other fibre types.

(iii). Type II X Fibres. Also called fast twitch, these fibres display similar contraction velocities to that of type II A fibres but fatigue at a much greater rate. Such fibres are found in large numbers in the muscles of the arms.

Activation of the different skeletal muscle fibres is directly related to the required task. For example, during low intensity or prolonged contractions, only type I fibres will be activated. If a stronger contraction is needed, type II A fibres are activated and if a maximal contraction is required, type II X fibres are triggered. Activation of each muscle fibre is controlled by neurological signals from the brain and spinal cord which control the release of chemicals necessary for cross bridge cycling. During prolonged resistance training periods research has shown that there is transformation in the muscle fibres from type II X to type II A (Staron *et al.*, 1994). Extended endurance exercise can result in transformation in the muscle fibres from type II to type I (Billeter & Hoppeler, 1992).

1.2.3 Muscle fibre performance characteristics

Muscle fibre exhibits two important performance characteristics i.e. the length-tension and force-velocity relationships that are well documented in physiological literature. The length-tension relationship has been developed from detailed studies of the characteristics of individual sarcomeres (Edman & Reggiani, 1987). This relationship states that the force produced in a sarcomere is directly related to the length of the fibre at that instant as shown in Figure 1.5 (Gorden *et al.* 1966).

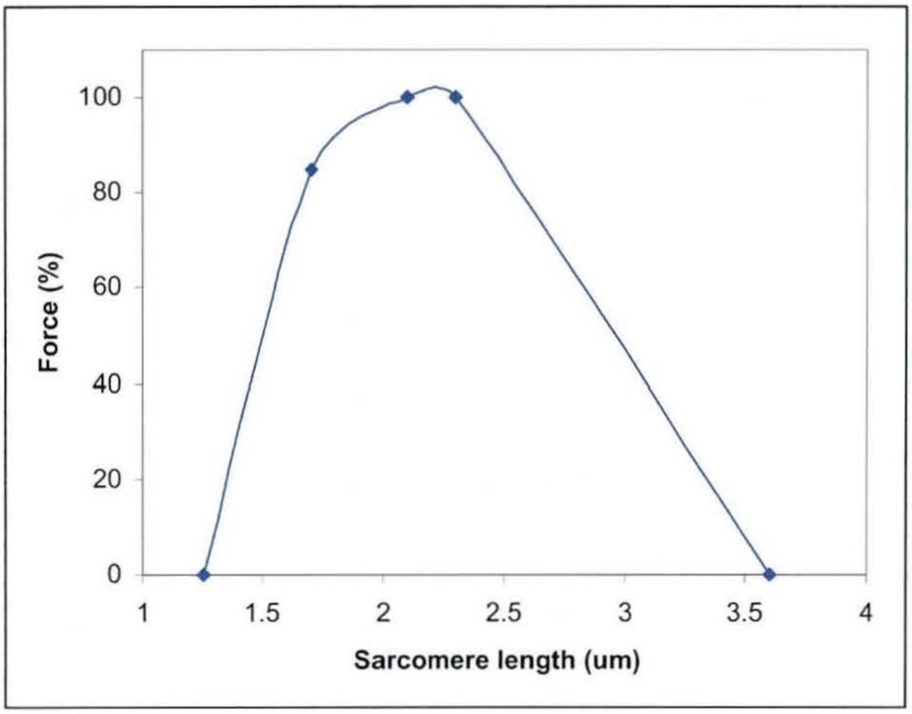


Figure 1.5: Relationship between force and length for an isolated sarcomere. Reproduced from Gorden *et al.*(1966).

The overall force produced by a muscle is proportional to its cross sectional area. Given that the sarcomeres are arranged in parallel within the muscle, and increase in area should imply a direct increase in the number of sarcomeres at that point and therefore increased ability to exert force (Jones & Round, 1990). Force is independent of muscle length because any number of sarcomeres arranged in series will only produce the same force as one sarcomere.

The second muscle fibre performance characteristic is known as the force-velocity relationship. Fenn and Marsh (Fenn & Marsh, 1935) were the first to demonstrate that this relationship existed when they observed that the force sustained by muscle rapidly decreases as the velocity of shortening increases. Eventually a velocity can be reached at which no force will be produced. This basic relationship, which is commonly referred to as the "Hill curve", has been widely referenced in literature and was originally collected during testing of a whole frog muscle (Hill, 1983). A simplified force versus velocity profile for an isolated muscle is shown in Figure 1.6.

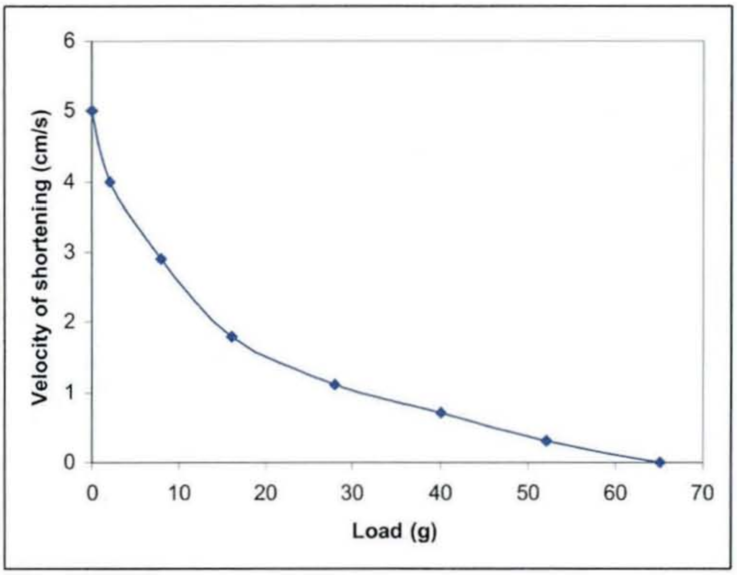


Figure 1.6: Relationship between force and velocity for an isolated muscle.

Work on the effect of velocity of lengthening (Edman, 1988) has shown that, at low speeds, the maximum muscle load capabilities remain relatively linear. As the velocity of lengthening increases there is marked rise in load resistance which is followed by a steady decline as the velocity approaches a limiting value that is equal to or greater then the cross bridge cyclic rate. This phenomenon can be identified in muscle group testing as shown in Figure 1.7 (Jorgensen, 1976), which clearly shows the effects of velocity of lengthening upon load capabilities.

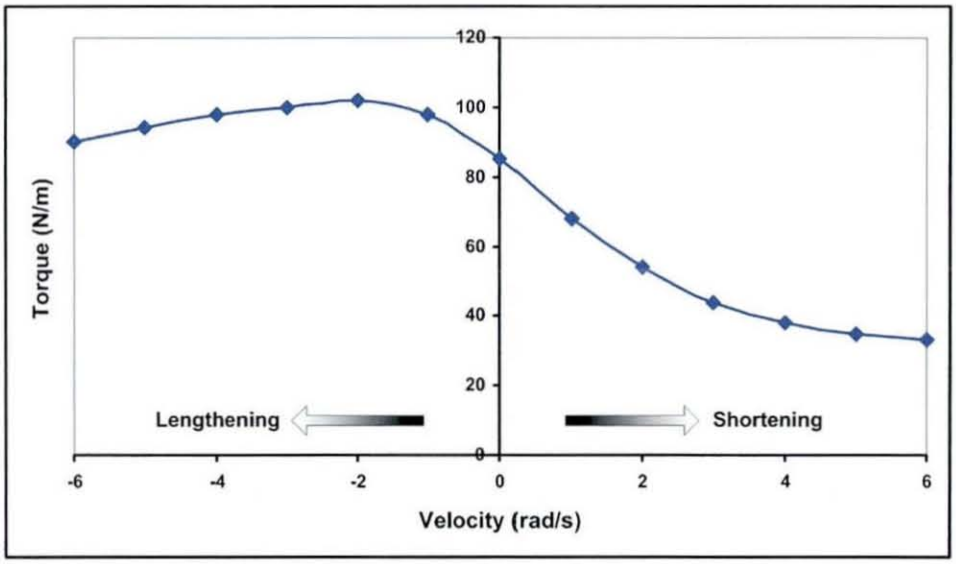


Figure 1.7: Resultant force and velocity relationship for the muscles of the elbow during lengthening and shortening. Reproduced from Jorgensen (1976).

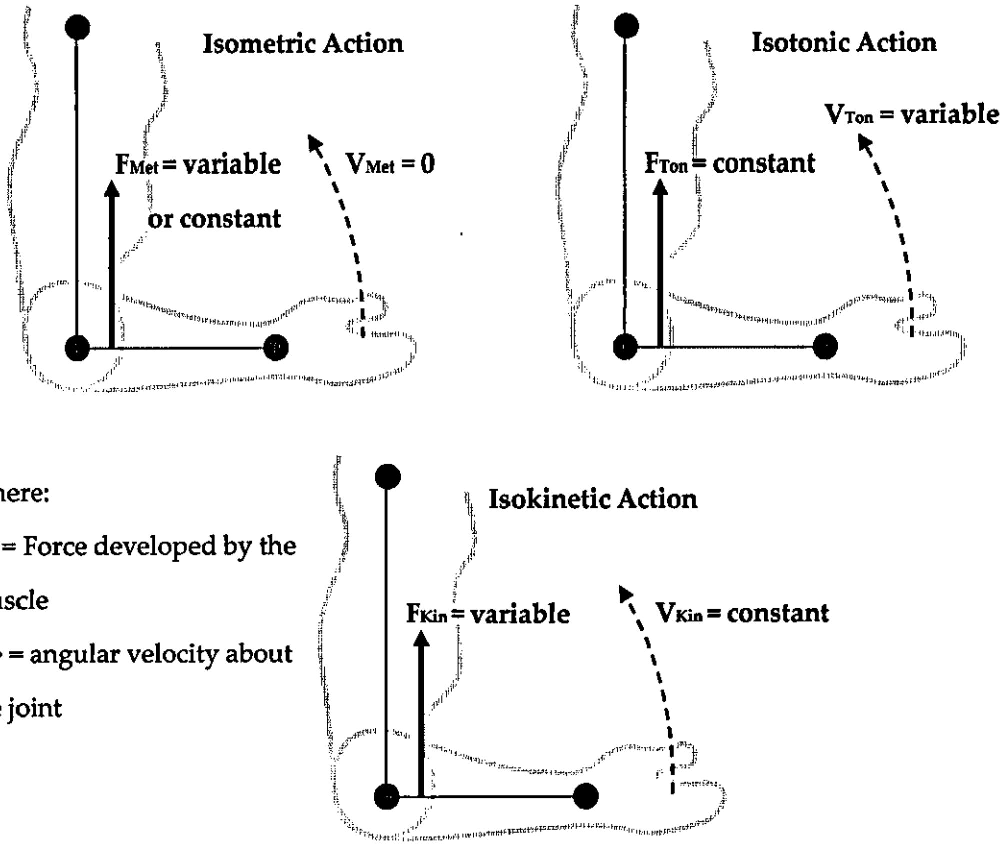
Fatigue is another important muscle characteristic, which can be defined as "a reversible decrease in contractile strength that occurs after long-lasting or repeated muscle activity" (Edman, 1992). Fatigue also limits the muscle's speed of shortening resulting in maximum reduction of around 35% (Edman and Mattiazzi, 1981). Muscle fatigue occurs in the muscle fibres due to a build up of waste products which have the following effects on cross-bridge parameters (Edman, 1992).

(i). Slight decrease in the number of interacting cross bridges
(ii). Reduced force output of the individual cross bridges
(iii). Reduced cross bridge cycle rate

Fatigue is an important consideration for accurate monitoring of performance and rehabilitation gains. Understanding of the influence of this degradation is essential for the prevention of incorrect exercise prescription and injury detection.

1.2.4 Classification of muscle fibre actions

Muscle fibre actions are generally classified in literature according to three well-established categories: isometric, isotonic, and isokinetic as shown in Figure 1.8. An isometric action occurs when the muscle produces a force, F_{Met}, but the limb system experiences no associated rotation about the joint (i.e. the user pushes / pulls against an immovable force). The most common muscle action category experience during most everyday activities is isotonic. Isotonic actions describe the particular behaviour where the muscle provides a constant force, F_{Ton}, regardless of the rate of change in length, V_{Ton}. An isokinetic action refers to a motion during which a constant rate of change in length, V_{Kin}, is maintained regardless of the force produced, F_{Kin}. Other forms of muscle action have been suggested but are debatable in their classification and generally form subsets of the three major groups.



Where:
F_{***} = Force developed by the muscle
V_{***} = angular velocity about the joint

Figure 1.8: Diagram of the three common muscle fibre actions, isometric, isotonic and isokinetic.

Isokinetic and isotonic actions can be sub-divided into concentric and eccentric movements according to the precise state of the muscle during motion. The difference between concentric and eccentric muscle actions within the context of a typical limb arrangement is illustrated in Figure 1.9. Winter (Winter, 1979) defines concentric movement as "that where the muscle force acts in the same direction as the angular velocity of the joint". At a muscular level this definition represents a change in length, V_{Con}, in the same direction as that of the resultant force, F_{Con}, thereby shortening the fibre. An eccentric action occurs when the angular velocity, V_{Ecc}, of the joint is in the opposite direction to the force applied by the muscle, F_{Ecc}. Eccentric movements usually occur when an external force is applied to the muscle which is greater than the force produced during contraction thereby lengthening the fibre.

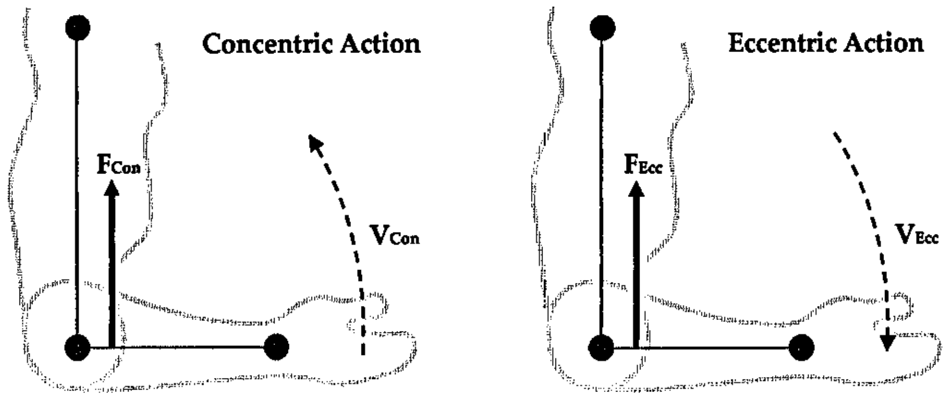


Figure 1.9: Diagram of the concentric and eccentric muscle actions.

These muscle action definitions are commonly used when referring to exercise motions (Wiksten & Peters, 2000) but direct application of these terms is scientifically incorrect. For example, isotonic exercise is described as an action with constant force production regardless of the rate of change of muscle length, however due to variations in skeletal lever arm arrangement with respect to joint angle, the muscle itself will not experience a constant load. When used in direct reference to particular joint exercises and measurements they represent the load and movement about the joint axis and not specific muscle performance. Further research in the implementation and testing of corrected muscle performance from these joint related figures could provide useful data, efficiently, for use within medical, academic and professional sports institutes.

1.2.5 Biomechanics of human movement and force production

Knowledge of the biomechanics of human movement and force production is essential for correct configuration of training systems. The interaction of muscle fibre characteristics and anatomical structures gives rise to unique relationships between force production and joint position of different human limbs. The basic biomechanical arrangement for motion is characterised by two skeletal levers, connected at a pivoting joint, activated by a muscle supported between the two by means of the connective tissue. Contraction of the muscle causes a reduction in the distance between the two skeletal connection points. Linear contraction of the muscle results in rotational movement of the skeletal actuators about the pivot point.

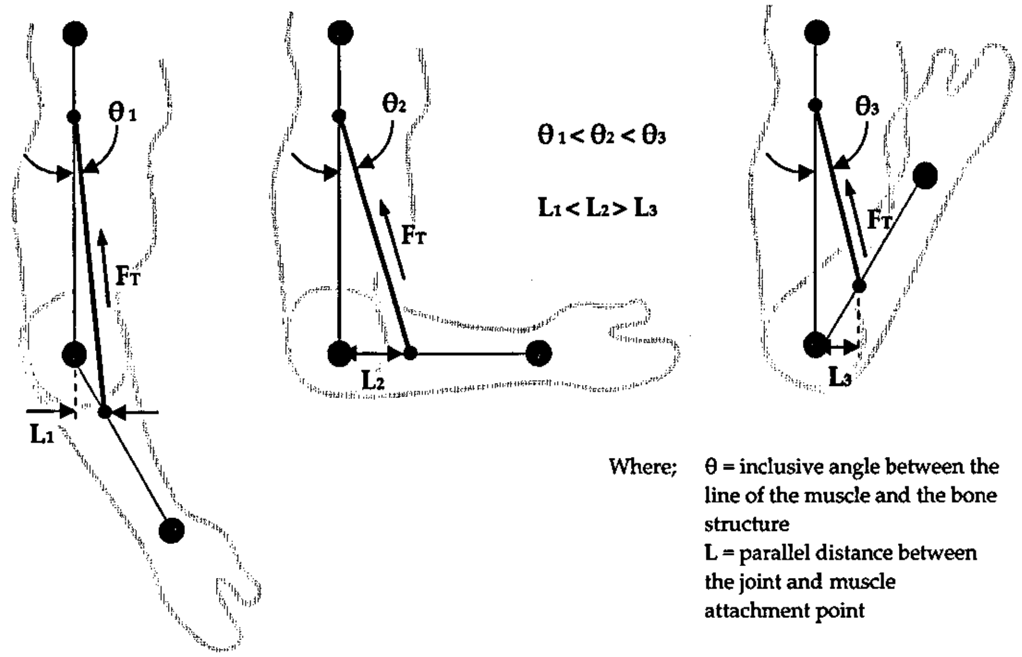
These rotational motions due to the applied force of the contracting muscle form the basis for the production of movement in all human limbs through the production of a resultant torque about the pivot.

Force production and loading of human limbs can be seen to replicate the arrangement of simple mechanical lever systems. These lever arrangements can be categorised into three main types (Harman, 1994):

(i). First-class. A first class lever system is characterised by the position of the opposing muscular force on the opposite side of the fulcrum to that of the applied load.
(ii). Second-class. Second class lever systems comprise of a muscular force which acts upon the same side of the fulcrum as the applied load. The perpendicular distance at which this muscular force acts from the fulcrum is greater then that of the applied load.
(iii). Third-class. Third class lever arrangements have an identical force arrangement to second class levers. However, the muscular force in third class levers acts at distance from the fulcrum which is smaller then that of the applied load.

During motion the perpendicular distance between the point at which the muscular force is transmitted and the fulcrum point changes L_1-L_3, (see Figure 1.10). This change in perpendicular distance also occurs for the applied load, D_1-D_4, due to the mechanical construction of the human limb lever systems and the fulcrums about which they operate (see Figure 1.11). As the lever system moves against the applied load, the angle at which the muscular force acts alters. Therefore, resistance to the applied load, F_L is only provided by a component of the actual muscular tension, F_T, as given in the following formula:

$$F_L = \cos\theta \times F_T \qquad (1.1)$$



Where; θ = inclusive angle between the line of the muscle and the bone structure
L = parallel distance between the joint and muscle attachment point

Figure 1.10: Variation in perpendicular distance between the joint and muscle attachment point, and force activation angle changes in relation to joint position.

Alterations in the angle and perpendicular distance between the activated muscle and the pivot point also lead to changes in velocity. At high perpendicular distances and angles, rotational displacement of the skeletal lever per unit of muscle contraction is reduced due to the geometric properties of the system. As these values reduce, muscle contractions result in increased displacement. Therefore, for a given time period the velocity of action at high distances and angles is less then that attainable at small distances and angles (Gowitzke & Milner, 1988).

The exact magnitude of force and velocity that can be transmitted by any individual through these lever systems is fundamentally based upon their precise anatomical and genetic configurations. Muscular, neurological, hormonal and skeletal system characteristics for force and velocity generation are dependent upon age, gender and general body size (Harmen, 1994). Therefore, the relationship between torque generated and the angle between the skeletal levers is not linear but forms a unique profile.

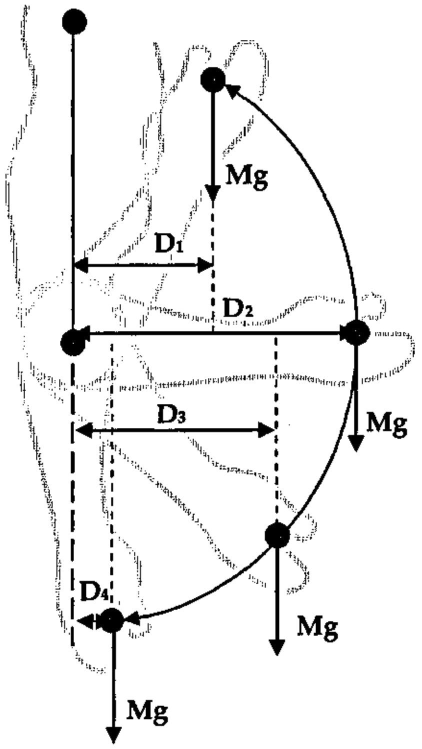


Figure 1.11 Variation in perpendicular distance between the joint and applied load with respect to joint position. Reproduced from Harmen (1994).

1.2.6 Muscle performance and measurement

Muscle performance and measurement was initially used as a demonstration of physical prowess. Capabilities where assessed upon the maximum weight that could be lifted for a given movement. Detailed performance monitoring programs have evolved from specific weight training applications into the public domain. As measurement techniques have developed two fundamental muscle performance characteristics have emerged: strength and power (Kulig *et al.*, 1984). Muscle strength is widely accepted as the ability of the muscle to produce force, although precise definition of this performance measure differs. For practical measurement of strength, Atha (Atha, 1981) suggests that strength is "The ability to develop force against an unyielding resistance in a contraction of unrestricted duration". Using this definition is much simpler as performance is primarily based on the force applied against an external resistance. As exercise and measurement equipment has evolved to include isokinetic testing, the definition of strength has been modified further. Knuttgen and Kramear (Knuttgen & Kramear, 1987) developed a more constrained definition with reference to the velocity of any muscle action thus, "strength is the maximal force that a muscle or muscle group can generate at a specified velocity".

The measurement of power as a quantitative means for muscle performance assessment has become common in commercial applications. Power is precisely defined in scientific literature as "the time rate of doing work" (Meriam, 1978), where work is the product of the force applied on an object and the distance that the object travels in the direction of the applied force. The common definition of power, P, is the product of the force applied to an object, F, and the velocity of the object in the direction of the applied force, V. Thus;

$$P = F \times V \tag{1.2}$$

The measurement of strength and power are closely related. Strength provides a measure of the capacity of the muscle to generate a force at a given speed. Power however, provides an exact mathematical relationship for the product of force and velocity. Perrine and Edgerton (Perrine & Edgerton, 1978) established the relationship between muscle power and velocity as shown in Figure 1.12. This relationship differs greatly from the declining trend displayed by the muscle force-velocity profiles (see section 1.2.3). The magnitude of power that a muscle can generate can be enhanced by increasing the force produced during a contraction at a given velocity. Increasing the velocity capabilities of the muscle may lead to a small increase in power but any improvements will be fundamentally restricted by the force-velocity relationship. Therefore, in order to develop power, a specific program of strength training at differing velocities is likely to result in an overall increase. Maximum power benefits can be achieved by strength training at relatively high velocities which will improve the level of force development and maximise the product sum.

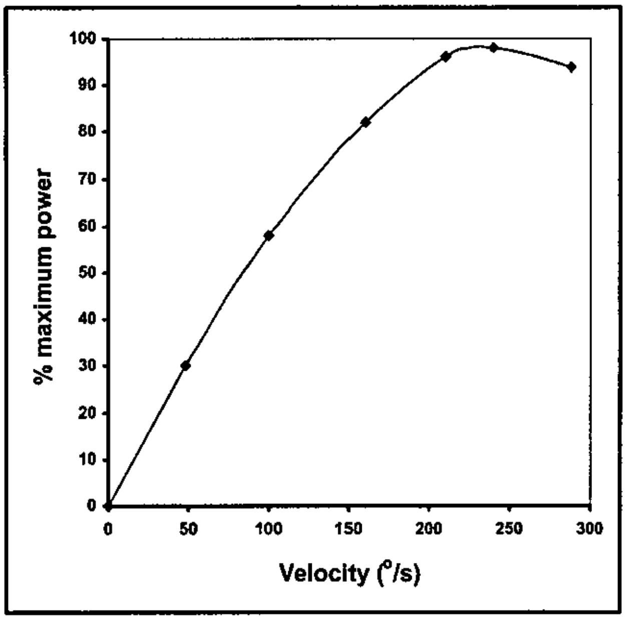


Figure 1.12: Power-velocity relationship of human muscle.

The most common method for quantitative assessment of strength is the maximum weight that a person can lift. Testing such as this is usually based upon a single full repetition using correct form at a load which is sufficiently high that a second full repetition can not be completed. Testing using this procedure has become known as the repetition maximum (RM) method (De Lorme, 1945). This value indicates the maximum weight that can be lifted, where *n*RM represents number of repetitions to maximum, such that *n* repetitions at this load can be completed but *n* +1 is not possible.

The process of completing a lift with a maximal load can be both disconcerting and dangerous for inexperienced individuals. In order to determine the one-repetition without undertaking such a high risk activity, various algorithms have been proposed to provide a theoretical method for predicting the maximum value (Brzyki, 1993; Epley, 1985; Lander, 1985). These equations use the total number of repetitions that can be completed with a sub-maximal load to estimate the one repetition weight. The accuracy of these formulas is dependent upon the muscle group tested and the number of repetitions completed. Where possible, it is recommended that these measurements should be used for relative comparisons and not absolute representations.

Basic power measurements can be calculated using this technique given the maximum load lifted, the distance over which the load was displaced and the time taken for the load to travel this distance. These values of power represent an average figure over the complete repetition and thus provide little information about important performance factors during the motion.

The 1-RM testing method is based upon dynamic isotonic action of the muscle, however Clarke carried out one of the first detailed studies of static isometric muscle strength using a cable tensiometry (Clarke *et al.*, 1950). These tests can be performed at different joint angles such that the recorded data points can be used to identify the strength-position relationship for maximal or sub-maximal actions. Similar studies were made using strain gauges to measure force (Wakim *et al.*, 1950) and modern measurement equipment such as dynamometers still provide the functionality for these isometric tests. Isometric strength curves created using these measurement devices are principally a product of interactions between the length-tension relationship of muscles tested and the variation of lever systems with joint angle. Note that isometric test data provides no information for power measurements as the velocity component is zero.

Technological developments in performance testing systems have resulted in a relatively new technique for strength determination. Pneumatic, hydraulic or electromechanical devices commonly termed as isokinetic dynamometers provide the capability to test muscle force production at a constant motion velocity during concentric or eccentric muscle actions.

Initial user force inputs results in the implementation of a pre-defined constant velocity profile. During the constant phase, maximal or sub-maximal force can be recorded over the test range of motion. Thus force-position relationships can be established over a range of known angular velocities (Kulig *et al.*, 1984). The precise profile of these relationships is believed to be principally based upon the force-velocity characteristic of muscle fibres with an underlying variation due to physical joint position. Power can be calculated over a range of constant velocities to determine potential strength training improvements. The data collection facilities also allow variations in power during a single repetition to be identified and any deficits rectified.

Generally, muscle performance measurement devices such as the tensiometer (Clarke *et al.*, 1950) or dynamometers record the resultant torque exerted by the muscle group through the skeletal system against an external resistance. This technique of strength measurement is used as the data translates directly to the operational parameters of the system and thus can be easily measured. Such measurements always assume that the axis of rotation of the external resistance is the same as that of the joint under investigation.

Strength data obtained during isotonic, isometric and isokinetic test conditions do not give rise to a single common value for maximal performance due to the characteristics of the muscle force-velocity relationship. Predicting values using data from different test protocols is generally unadvisable due to variations in the magnitude of interaction between different muscles within a group during different actions and the effect of this upon the recorded strength data (Knapik *et al.*, 1983).

The measurement of strength using the resultant torque provides limited information about the force produced by an individual muscle because precise movement normally involves the control and activation of a group of muscles with varying mechanical arrangements and muscular composition. Research undertaken by Chang *et al.* (1999) found that the muscles involved in elbow flexion developed their maximum forces at different joint angles as shown in Table.1.2.

Muscle Name	Joint Angle/ °
Biceps Brachii	107.49
Brachialis	97.88
Brachioradialis	48.49

Table.1.2: Joint angles of maximal force produce for a range of muscle groups about the elbow joint. Reproduced from Cheng *et al.* (1999)

Thus, the force-position relationship recorded about any given joint is the result of the combined force contributions of each muscle. The resultant force profile as a product of the combination of muscles within a muscle group can be illustrated using isometric data as shown in Figure 1.13 (Jones *et al.*, 1989).

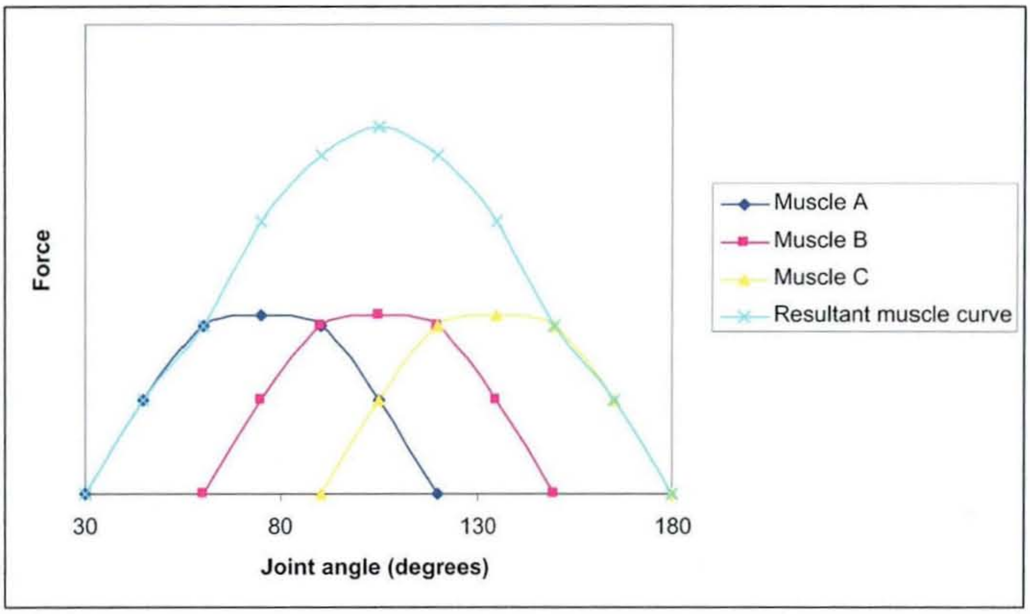


Figure 1.13: Resultant force profile as a result of the combined interaction of three separate muscles. Reproduced from Jones *et al.* (1989).

The weight and inertial effects of body parts and passive structures such as ligaments and cartilage are not isolated in these strength curves. Therefore, it should be noted that established methods for the assessment of muscle performance provide only a relative measure of the true capabilities based upon the resultant force developed at the activation point. Data regarding individual muscle functionality is restricted due to practical test considerations.

Although isolated fibre responses cannot be measured easily, current measurement techniques provide a useful tool for overall performance development. Research conducted by Signorile and Applegate (Signorile & Applegate, 2000) aimed to enhance these performance measures by combining torque, angle and speed data in a three-dimensional surface map as shown in Figure 1.14. These surfaces provide information on the basic length-tension and force-velocity characteristics of the muscle group but also display the interactions of these parameters over their entire range. Through a process of detailed data collection the information in maps such as these could be used to accurately identify specific athletic performance characteristics and training programs, specify general exercise regimes and improvements and highlight injury or rehabilitation deficits.

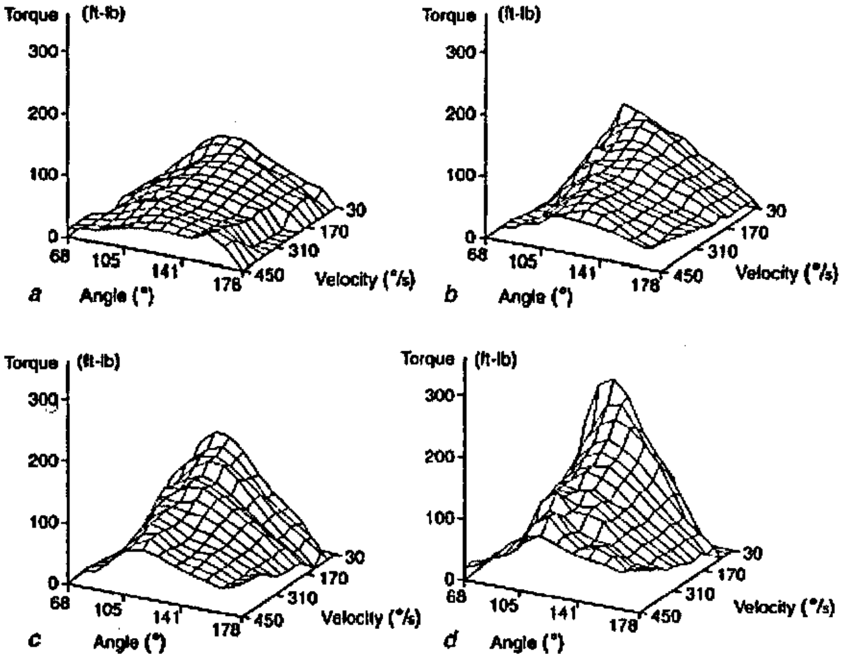


Figure 1.14: Three dimensional exercise maps demonstrating the relationship between joint angle, velocity and torque. Reproduced from Signorile & Applegate (2000).

1.2.7 Aerobic exercise principles

The cardiovascular and respiratory systems form the main aerobic functional components which include the heart, lungs, blood vessels and blood in the human body (Wilmore & Costill, 2004). These organs are responsible for transporting oxygenated blood from the lungs to points of demand such as muscles. The system must then regulate the flow of deoxygenated blood from around the body back to the lungs to perform a gaseous exchange of unwanted carbon dioxide for fresh oxygen. The operation of this system is essentially a subconscious co-ordinated activation of muscle groups and therefore the basic muscle development principles discussed previously are also relevant in this context.

Although the bio-chemical and neuropsychological processes differ slightly from anaerobic exercise, aerobic exercise such as walking, cycling and rowing allows the principle of overloading (see section 1.3) to be applied to the cardiovascular system. Characterised by a low to moderate intensity and high volume (Potteiger, 1994) there are a number of benefits associated with this type of training. Strengthening of the muscles associated with respiration and circulation increases the flow of air into and out of the lungs and improves the efficiency of the heart respectively. An increase in the number of red blood cells and enhanced storage of energy molecules leads to greater oxygen transportation and increased endurance. Aerobic exercise has been shown to be influential in reducing the risk of cardiovascular related illness such as hypertension whilst aiding in the prevention of general health related conditions such as diabetes and obesity (Department of Health, 2004).

1.2.8 Adaptations to exercise stimuli

The muscular and neural capabilities of the human body are known to vary depending upon the biomechanics of the surround joints and the operational conditions. Research has shown that repetitive and prolonged alterations in the load or velocity demands of a given muscle group results in a number of biological adaptations as a natural response to minimise risk of injury. Adaptations recorded during active overloading of muscle groups is generally categorised into three systems; skeletal, neurological, and hormonal. The alterations that occur in these elements produce a resultant increase in the muscles force and / or velocity generation capabilities depending upon the particular input stimulus.

1.3 Exercise training methodologies

The effects of aerobic / anaerobic training and subsequent biological adaptations vary depending upon the particular training variables selected (see below), the combination of these parameters during single training session and the distribution over an entire training period. The design of a training system can be focused to provide specific physical responses. Exercise equipment must ensure that the range of exercise methodologies are supported and enhanced through intuitive design and operation procedures. The main acute training variables of single exercise sessions are (Fleck & Kraemer, 1987):

(i). Choice of exercise. Correct exercise selection ensures that the desired muscle groups are trained appropriately based upon the needs of the user.

(ii). Order of exercise. The order of the prescribed exercise has important implications on performance. Exercise movements for training larger muscle groups, such as chest press, generally require synergistic activation of the smaller muscle groups. These smaller groups can become exhausted prior to any specific training exercises. This anomaly is commonly known as pre-exhaustion.

(iii). Exercise intensity. The magnitude of load, commonly termed the intensity of an exercise, is crucial in anaerobic training (McDonagh & Davies, 1984). Precise selection of load based upon the exercise chosen and the required training response is fundamental in determining the magnitude of the gains to be achieved.

(iv). Exercise volume. Exercise volume is a product of the number of repetitions and number of sets completed during a given period. Exercise volume is directly related to intensity and must be selected to support the specific training goals of the individual (i.e. strength, power, endurance).

(v). Rest periods. Rest periods relate to the inactive time between each exercise set and also between complete training sessions. These periods must be specified to ensure that sufficient time is given for recovery.

(vi). Speed specificity. The speed of motion for a given exercise should represent those experienced during normal activities. General users are likely to exercise at an intermediate to low speed whilst sports professionals might benefit from much higher velocities.

Continued monitoring and updating of these acute variables over complete training periods is important in achieving optimum exercise responses (Fleck & Kraemer, 1987). Simple "periodisation" methods utilise a linear approach which monitor the maximum capabilities of the individual and make systematic increases in intensity or volume with respect to improved performance. Although processes such as this provide valid gains in performance they do not allow the integration and adjustment for competition preparation and recovery, overtraining and exercise familiarisation.

A periodisation model has been established which provides the required performance gains through a variable training structure. Originally proposed by Matveyev (Matveyev, 1981) in 1981 and later developed by Stone and O'Bryant (Stone and O'Bryant, 1987), this system is based upon a three tier hierarchical arrangement of repetitive cycles known as macro, meso and microcycles respectively. The macro cycle refers to the overall training period and focuses upon the final performance goals which may be set over a period of, for example, four months to four years. This period is separated into a number of mesocycles which represent the intermediate goals of the individual or important competitions at which performance must be optimised.

The mesocycles are sub-divided into periods of preparation, transition, competition and recovery phases. During the preparation phase, training is focused on the development of a base level of fitness. At the beginning of this period the initial aim will be hypertrophy of the core muscle groups. Once the underlying level of fitness has been achieved, strength training and sports specific power routines can be introduced. The transition phase forms the intermediary period between the general training sessions conducted during the preparation phase and the high intensity, low volume, sports specific activities of the competition phase. The recovery phase consists of non-specific, non-resistance unstructured exercises which are designed to maintain overall fitness whilst permitting recovery from the competitive phase. Each of these phases may consist of single or multiple numbers of microcycles, which provide specific training programs and variable levels for that particular phase. Each microcycle is generally around 1-2 weeks in length. Successful development and implementation of periodisation programs requires a reasonably advanced level of knowledge of training theory and therefore are generally only utilised by medical staff and sports professionals.

1.3.1 Training system classification

A number of standardised training methodologies based upon these variables have been established and documented in general literature through practical testing and basic knowledge of the relevant physiological requirements and effects (Fleck & Kraemer, 1987), see Figure 1.15. However, it should be noted that the exact selection and arrangement of these parameters is primarily dependent upon the individual's wishes, health status, fitness level and objectives and may be influenced by input from training / rehabilitation professionals.

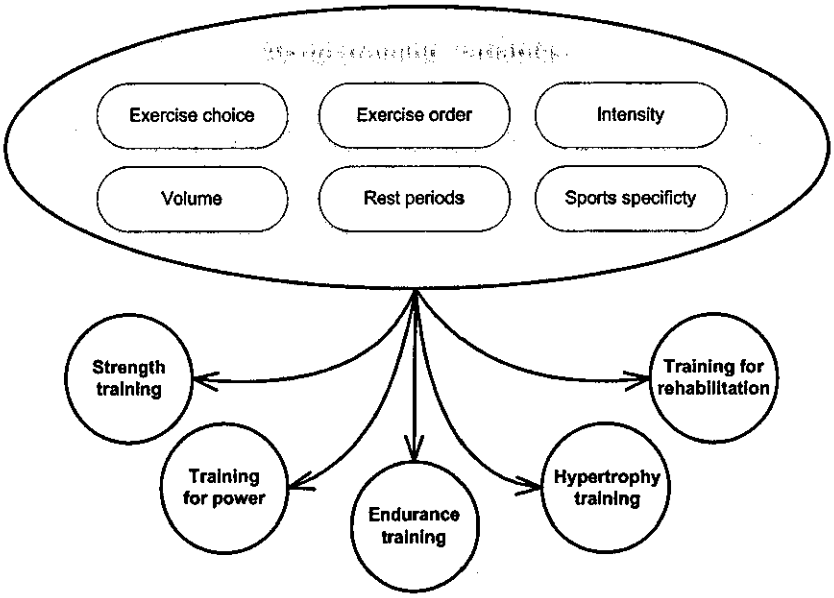


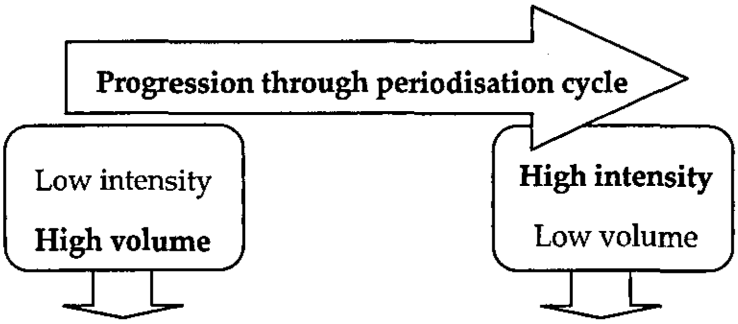
Figure 1.15: Training system classification.

Sports specific training systems exhibit specific characteristic that are closely matched to the particular motions experienced during match play and therefore it is difficult to generalise the structure of these sessions. However, the remaining training systems can be expressed using the acute variables discussed in section 1.3. Table 1.3 lists the main training systems together with common parameter levels prescribed for each category.

Training system	Load assignment (%1RM)	No. of repetitions	No. of sets	Rest period (s)
Strength training	80-90	3-10	3-5	180-300
Training for power	60-80	3-10	3-5	30-60
Hypertrophy training	60-90	6-10	3-5	30-60
Endurance training	40-80	20-100	3-5	30-60
Training for rehabilitation	5-40	5-20	1	-

Table 1.3: Acute variable characteristics for common training systems.

The precise design of each training system can be calculated using the two basic variables: intensity and volume. The relationship between these elements is related to the periodisation model and is primarily based upon the position of the training session within the macro, meso and micro cycles. Using the periodisation principles, exercise intensity is initially set at a low level while volume is maximised. As the cycle progresses, the intensity is gradually increased as the volume is reduced. During a rehabilitation cycle, the aim of the exercises is to increase both intensity and volume over and extended period of time. Figure 1.16 shows an example of the variation in intensity and volume levels over the duration of a periodisation cycle.



Training system	Load assignment (%1RM)	No. of repetitions	No. of sets	Load assignment (%1RM)	No. of repetitions	No. of sets
Strength training	80	10	5	90	3	3
Training for power	60	10	5	80	3	3
Hypertrophy training	60	10	5	90	6	3
Endurance training	40	100	5	80	20	3
Training for rehabilitation	5	5	1	40	20	1

Figure1.16: Variation of exercise load and intensity using periodisation principles.

1.3.2 Training for strength

When training for strength it is important to consider the underlying principles of the exercises that are prescribed to ensure that the desired biological responses are achieved (Fleck & Kraemer, 1987). The basic strength training principles for each type of muscle fibre action and the different systems that have been built around these principles are described in the following sections.

1.3.2.1 Strength training principles

Strength training for increased maximum muscular force is based upon a number of important principles and correct application of these principles should lead to effective development of the muscule related systems. The fundamental strength training principles are:

(i). Overload. In order to develop the maximum amount of force that a muscle can produce it must be overloaded or stressed beyond its normal limit. Stimulating the muscle in this manner requires additional load to be applied to the structure beyond that experienced during normal activity. This process of overloading initiates biological adaptations as the body attempts to adjust to these new environmental conditions (Williams *et al.*, 2005).

(ii). Progressive Resistance. Once initiated, a program involving muscle overload will lead to continued adaptation until the changes in structure are acceptable for the applied stresses. At this point further gains in maximum strength will cease. Therefore, the initial load must be increased to a new overload level, thereby creating extra stress within the muscle and further adaptations.

(iii). Muscle balance. An ideal strength training system should be designed to induce development in all of the major muscle groups. Where exercise is focused upon particular joints (for example sport, rehabilitation activities) it is important that all of the muscles about that joint are trained to prevent imbalance, reduced performance and avoid potentially serious injuries (Baechle *et al.*, 1994).

(iv). Specificity. Where possible, strength training should support the development of muscle groups used directly in sporting / rehabilitation activities and should replicate the movement, loads and speeds associated with these actions (Harman, 1994).

(v). Recovery time. In order for the body to recover from the physical exertion of a training session, it is generally recommended that a rest period of 48 hours is taken between each session. However, this figure will depend upon the experience of the individual and the intensity and volume of the exercises (Fleck & Kraemer, 1987).

1.3.2.2 Isometric strength training principles

Claims by Hettinger and Muller (Hettinger & Muller, 1953) in the 1950's proposed that a single maximal isometric contraction lasting approximately six seconds would produce maximum strength gains. A review of isotonic and isokinetic exercise research has disproved this theory by demonstrating much greater strength responses then those achieved by isolated isometric tests (Atha, 1981). However, isometric exercise is more efficient and requires less training effort as the muscle is loaded maximally at every joint angle. Isometric testing generally produces smaller strength gains than other exercise systems and are isolated to the specific joint angle (Perrin, 1995; Wiksten & Peters, 2000) but allow accurate evaluations of the muscle to be made at specific positions.

The recommended duration of an isometric exercise ranges from one second to around ten seconds. The exact duration is dependent upon the number of contractions that are to be undertaken. Research by McDonagh and Davies (McDonagh & Davies, 1984) has shown that the product of training duration and contraction number is strongly related to overall training results. Therefore, it has been suggested that isometric exercise should consist of a high number of short duration contractions or a low number of longer contractions. In order to maximise training response it is recommended that these exercises should be conducted three times per week with a duration of three to five seconds and fifteen to twenty repetitions (Fleck & Kraemer, 1987).

1.3.2.3 Isotonic strength training systems

Isotonic exercise is the most common system used for strength training muscles (Wiksten & Peters, 2000). The basis component of isotonic exercise is the one-repetition maximum value. The training systems in Figure 1.17 represent routines commonly referenced in exercise literature and related media (Fleck & Kraemer, 1987). These provide a general structure for different systems based upon the variables stated in section 1.3.

Modern commercial isotonic training devices have adopted the concept of variable resistance. These systems have been designed to provide muscle overload at all joint angles thereby overcoming the effects of the physiological and mechanical structures upon the applied load. Commercial examples of variable resistance systems are based upon the insertion of a fixed mechanical cam profile into a standard weight based machine. While these devices do provide improved load-position relationships, academic and scientific bodies have questioned the benefits of such systems in regard to their inability to match the specific strength curves of users of different ages, genders and body compositions.

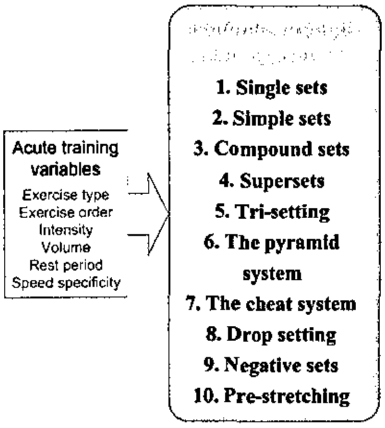


Figure 1.17: Isotonic strength training systems.

Experimental data has shown limited performance increases with commercial variable resistance devices when compared to traditional isotonic exercises (Stone *et al.*, 1979). Ideally an exercise system should be calibrated to the precise strength profile of the user. This curve can be used as a template for the applied load to ensure that the magnitude of muscle overload is optimised for each joint angle.

Detailed analysis of the strength curves of particular individuals may lead to the identification of common performance characteristics in specific groups of athletes. These optimised profiles might form the basis of variable resistance curves for developing future sports persons or dedicated members of the general population. Currently, no data has been recorded to determine whether it is possible to train towards a specific strength curve and also whether this may be advantageous.

Such changes are theoretically possible through specific adaptations in the muscular, neurological, and hormonal systems and changes in the interaction between the muscles within a particular group (Jones *et al.*, 1989). An increase in the performance of a single muscle would result in a change in the overall shape of the strength curve about the joint. This phenomenon has been demonstrated in Figure 1.18, the original force developed by muscle C (see Figure 1.16) has been increased causing the characteristics of the resultant curve to change. There is limited experimental data to support this hypothesis, but further research is required to establish the extent of development of specific characteristic of human muscle strength using customised variable resistance training profiles.

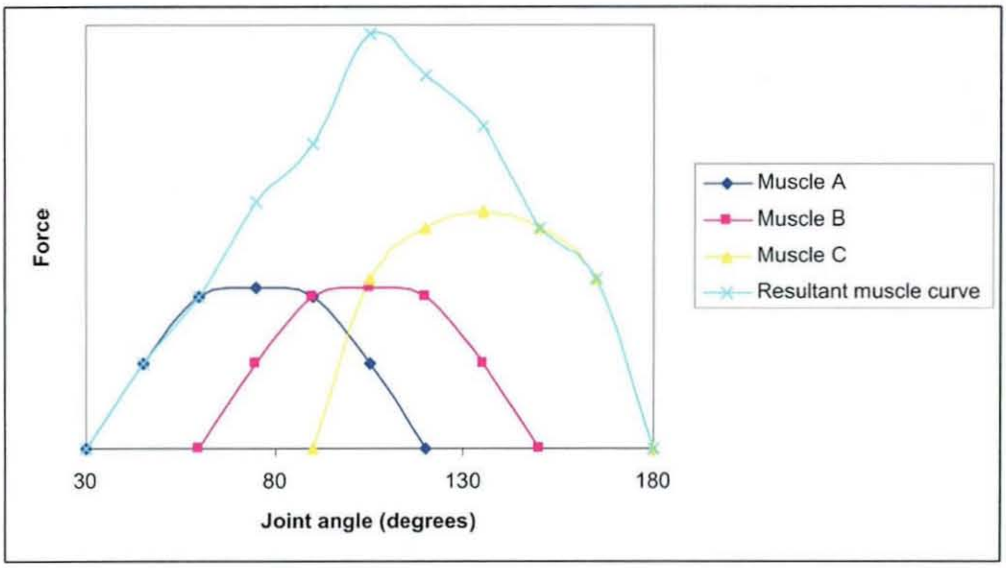


Figure.1.18: Developments in the overall force profile as a result of alterations in isolated muscle performance. Reproduced from Jones *et al.* (1989).

1.3.2.4 Isokinetic strength training systems

Isokinetic exercise allows maximal or sub-maximal force to be developed throughout the range of motion at a predetermined velocity (Perrin, 1993). As the muscle group is permanently overloaded throughout the duration of the exercise, an increase in overall strength can be expected when compared to isotonic exercise. However, research has failed to demonstrate that a significant change in strength can be achieved (Kulig *et al.*, 1984). The optimum exercise routine for isokinetic exercise is not rigidly defined as that for isotonic exercise (Kulig *et al.*, 1984). Different testing procedures have been developed according to the particular data requirements of the academic and scientific experimental teams.

A recommended routine (Perrin, 1993) includes: a sub-maximal warm-up for familiarisation at each velocity, exercise at slow velocity for thirty seconds, followed by exercise at intermediate velocity for thirty seconds and finally exercise at fast velocity for thirty seconds. For the purpose of strength training, there is some disagreement as to the optimum exercise velocity (Perrin, 1993). It has been proposed that a wide range of velocities should be used to maximise overall training response or alternatively that only low velocities should be used as they allow the user to produce maximum force. The precise order of eccentric and concentric actions and the effect upon strength have received limited research (see section 1.3.4).

1.3.3 Training for power, sport specific movements, and endurance

Using the definition of muscle power outlined in section 1.2.7, the overall power exerted about a given joint during exercise is determined by the product of the resultant force and the joint angular velocity (Winter, 1979). Generally, increases in power are achieved through normal strength training exercises. Adaptations due to these training inputs lead to an increase in the force capabilities of the muscle and consequently an increase in power.

Power may also be developed through an increase in the velocity at which a given load can be moved. Muscle contraction velocity is directly related to overall length and also composition based upon fibre type as discussed in section 1.2.2. The rate of change of length in a muscle is determined by the number of sarcomeres in series. Therefore, greater length as a result of an increase in the number of sarcomeres should result in an increase in power. It has been suggested that small adaptations such as this may be achieved by stretching exercises (Jones *et al.*, 1989).

Resistance exercise as a sports training technique uses a principle known as specificity (Harman, 1994). Specificity refers to the process of selecting particular exercise parameters to suit the needs of the athlete and their sport. The aim of this type of exercise is to develop the skilled motions that an athlete performs during competition using representative training movements. These movements are based on basic strength and power exercises which are adapted to suit the individual. The systems selected should activate the appropriate muscle groups using representative loads and velocities that are experienced during normal sporting activity.

Practical experience has shown that resistance training using sports specific training produces maximal performance results when testing protocols simulate the sports activity. These findings are being supported by research which indicates changes in the force-velocity curves as a result of adaptations through sports specific training systems (Signorile & Applegate, 2000). It should be noted that the adaptation and performance increase capabilities of a person in response to a specific sports orientated program are fundamentally limited by their genetic structure. It is unlikely therefore, that a completely untrained individual can become a leading performance athlete through the simple application of sports specific training systems. Sports specific training generally involves replicating the compound movements experienced during competition whilst additional resistance is applied using free weights or weights machines. Accurate replication, control and monitoring of the velocities and forces encountered during these activities can not be achieved with current exercise systems (see Chapter 2).

Endurance is the ability to maintain power over an extended period of time, thereby delaying the effects of fatigue (Jones & Round, 1990). Slow twitch muscle fibres have been shown to exhibit much greater fatigue resistance then fast twitch fibres. Muscular endurance training systems generally involve sub-maximal contractions which are conducted at average velocities for a relatively high number of repetitions with short rest periods. Training periods range from around five minutes up to a number of hours at loads of between 40-80% of the 1RM (Potteiger, 1994). Increases in muscular endurance with respect to adaptations of the musculoskeletal system are generally a result of hypertrophy of type I muscle fibres, a reduction in type IIX fibres, proportional increase in type IIA fibres and also associated neurological changes. Improved fatigue resistance can also be also achieved through other muscular adaptations and primarily via functional improvements of the cardiovascular system (Williams, 1994).

1.3.4 Eccentric exercise

As discussed in section 1.2.4, eccentric training of a muscle refers to a lengthening of the fibre due to an external load of greater magnitude than that of the internal tension. Since maximum concentric strength potential is lower than that of eccentric strength (Hortobagyi & Katch, 1990), the relative weakness of the concentric action prevents a complete overload during the eccentric portion of the exercise and thus the full training benefits are not received. Ideally an optimally overloaded exercise should support a lower variable resistance as the weight is raised than when the weight is lowered. The inclusion of eccentric loading in nominal training programs has been shown to provide improved levels of strength gain when compared to pure concentric training (Häkkinen & Komi , 1981). The positive effects of eccentric training can be attributed to four key biological responses as shown in Figure 1.19.

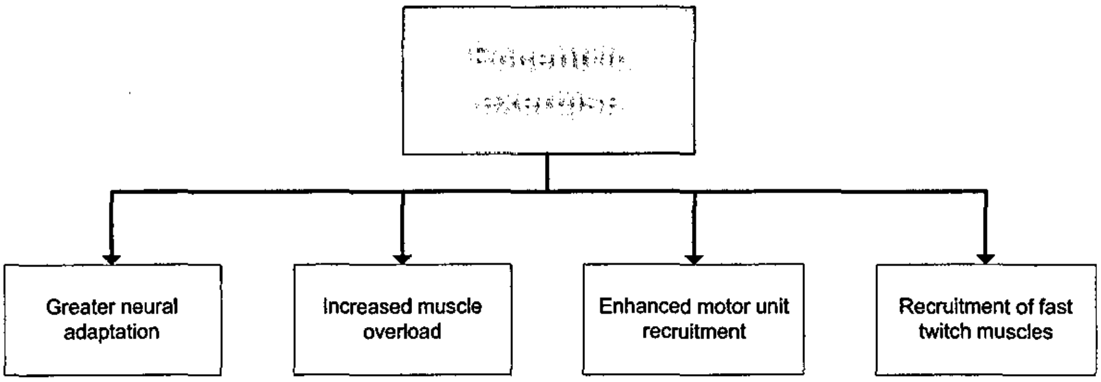


Figure 1.19: Training benefits of eccentric exercise.

A greater neural adaptation to eccentric training than to concentric training has been identified during testing (Hortobagyi *et al.*, 1996). The force output produced during maximal eccentric action is increased due to the higher external load, thereby promoting greater overload (Colliander & Tesch, 1990). A higher level of stress per motor unit during eccentric work has been found since fewer motor units are recruited during eccentric movements and hence each of the recruited motor units receives increased stimulation (Linnamo *et al.*, 2002). As a result, eccentric training can generate up to 1.3 times more tension than concentric training. Greater tension provides increased stimulus to the muscle fibres, which in turn encourages greater biological adaptations. Research has also indicated that maximal eccentric actions generally recruit fast-twitch muscle fibres, which are more responsive to muscle growth and strengthening (Hortobagyi *et al.*, 1996).

The benefits of eccentric training have been well researched and repeatedly show an effective increase in strength. For example, a study by Hortobagyi et al, (Hortobagyi *et al.*, 1996) found that the total maximal strength improvement from eccentric-only training resulted in greater strength gains than a concentric-only program. Eccentric training gave a mean improvement of 45% in post trial isometric strength tests, while concentric training led to an improvement of 36%. A study by Higbie et al, (Higbie *et al.*, 1996) found a combined strength increase (concentric strength improvement plus eccentric strength improvement) of 43% with an eccentric-only regimen compared to one of 31.2% with a concentric-only regimen. It was also found that omitting eccentric stress in a training program severely compromise the potential strength gains (Hater et al., 1991). These results are supported by a recent study (Farthing & Chilibeck, 2003) which concluded that eccentric training resulted in greater hypertrophy than concentric training.

1.3.5 Variokinetics

Following an analysis of the three-dimensional surface plots shown in section 1.2.7, it appeared that a novel form of muscle exercise could be identified which would allow the user to train to a specific range of velocities and loads as outlined by these relationships. The research conducted (Signorile & Applegate, 2000) identified differing force-velocity and force-angle characteristics for particular athletes. Therefore, it was proposed that the new exercise system could include a variable velocity / variable resistance feature which would allow a user to exercise along a specific path on the three dimensional maps. This multi-variable system could be used to provide true isokinetic and isotonic testing of muscle groups by varying the resultant joint variables such that the internal muscle groups experience constant force and velocity. The load could be varied to optimise the torque applied to muscle depending upon the instantaneous limb speed, thereby maximising muscle overload and physiological response to the exercise.

1.4 Summary

The fundamental muscular and neurological processes that provide movement of the musculoskeletal system have been discussed with reference to the two important properties displayed by muscle fibres: the length-tension and force-velocity relationships. These characteristics and the musculoskeletal lever systems are the main factors in the determination of the precise profiles recorded for resultant torque against joint angular position and velocity. The different muscle actions for consideration when developing the exercise system are isometric, isotonic, and isokinetic. Isotonic and isokinetic motions have been sub-categorised into concentric and eccentric actions according to the direction of the resultant joint velocity.

Careful selection of the exercise variables is required to optimise the desired training response. A system of progressive overload, using periodisation principles must be maintained to ensure continued development. Load intensity is known to be the main factor in muscle strength adaptation and that training to specific load or velocity curves can maximise performance response. Strength training principles can be applied in the development of power although the use of high movement velocities is recommended for optimal gains. Ideally, all muscle groups should be exercised to prevent imbalance and injury. Performance athletes may choose to utilise specificity concepts to match the requirements of their particular sport to the general training systems. Sufficient recovery time between exercise sessions must be given to enable complete recuperation from previous overload stimulations.

The most effective method for optimising strength gains is open to criticism. Therefore it is wise to include all forms of exercise and testing procedures into a complete training system to provide a range of performance measures and physical responses. The generation of user specific load and velocity profiles is considered an important area for further research, which must also consider the implementation of performance profiles and the magnitude of adaptation that can be achieved using such a system. A multi-variable training routine has been proposed which would be implemented and tested during the development of the exercise machine.

Chapter 2

Requirements definition and design specification

2.0 Introduction

In order to develop a system that will provide a step change in functionality, usability and cost, a detailed and comprehensive list of relevant requirements must be constructed. These requirements have been developed using knowledge acquired from the background exercise science research in Chapter 1, critical analysis of the existing designs and results extracted from user studies. Additional information regarding appropriate legislation and industry standards was collated together with general operational aspects. The relevant qualitative and quantitative properties extracted from these resources were used in the creation of the exercise system design specification document as shown in Figure 2.1. The system must fulfil the essential objectives of each of the training domains identified in order to be an accurate data collection tool and testing device for academic and medical research purposes whilst demonstrating the potential of a modular exercise platform for commercial and home based applications.

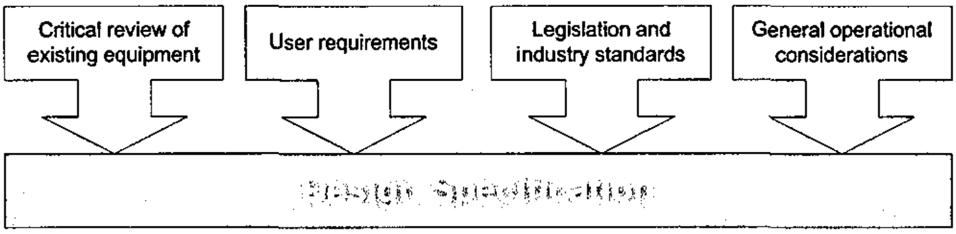


Figure 2.1: Information resources for the production of a detailed design specification for the modular exercise system.

2.1 Evaluation of existing exercise devices

The development of any new product must include a critical evaluation of the existing designs and technology. This ensures that crucial design features and de facto performance levels are maintained, whist inherent shortcomings are rectified. Consideration should be given to current and future governmental legislation and industrial regulations as the implications upon the design, production, operation and disposal of equipment such as that investigated during this research could be significant.

The categorisation of existing commercial exercise systems for assessment during this research is shown in Figure 2.2. General equipment can be classified coarsely as aerobic or anaerobic, with each sub-division consisting of a series of discrete devices which provide common training stimuli. Each of the mechanical and electro-mechanical solutions identified have been analysed in the following sections.

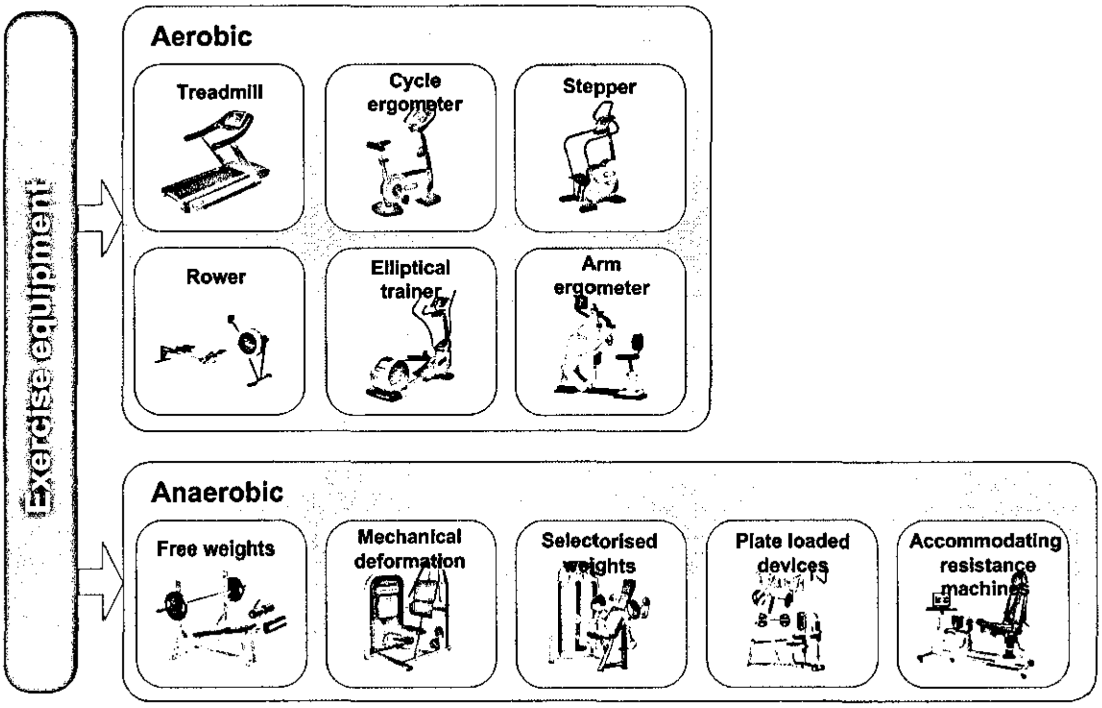


Figure 2.2: Categorisation of common exercise equipment for critical analysis.

2.1.1 Aerobic exercise equipment

The primary function of this type of exercise equipment is the provision of human machine interactions which encourage the user to exercise in an aerobic mode. These systems require the user to co-activate various groups of muscles for extended periods of time. These prolonged training sessions encourage the development of endurance characteristics as a result of increased: (i) cardiovascular performance, (ii) bio-chemical process alterations and (iii) muscular, musculoskeletal and neuromuscular adaptations. The motions and movement paths exhibited by these mechanisms generally replicate those experienced during habitual activities such as walking and cycling with an emphasis upon the recruitment of the muscles of the lower body.

2.1.1.1 Treadmill

The treadmill principally consists of an artificial surface which is supported between two rollers and driven by some form of electric motor. Using this "virtual track" the user is able to run or walk an essentially limitless distance in a single location without being exposed to the environmental conditions that are encountered when training outdoors. Market studies have shown that the treadmill is traditionally the most popular piece of exercise equipment in commercial gyms although the yearly growth in sales is beginning to decline (SGMA, 2002).

An impact exercise such as running encourages the development of skeletal strength which can be beneficial for participation in sporting activities. However, prolonged exercise using such a system can become detrimental due to the high joint and bone loading conditions and should be avoided by individuals with related impairments. Exercising in this manner not only helps to develop the cardiovascular system but induces muscular work over a large proportion of the anatomy thereby improving core stability and overall conditioning. Modern treadmills provide shock absorption methods to suppress the inherent peak forces that occur. The inclusion of adjustable surface incline facilities and programmable speed functions provide the user with the opportunity to create a wide range of training scenarios and enhance the realism of the exercise.

2.1.1.2 Cycle ergometer

The cycle ergometer has become the most successful and widely used item of aerobic home fitness equipment on the market with 14% of all people surveyed having a unit in their household (Mintel International Group Limited, 2003). This popularity is due to its relatively low cost, high durability and compact dimensions. Based on a stationary bicycle with traditional bars and saddle, resistance is provided by means of a frictional, magnetic or pneumatic braking mechanism. Cycle ergometers isolate muscle activation to the lower body region and are classified as non-impact devices. Rudimentary control facilities allow the resistance to be adjusted automatically to replicate the varying conditions that may be experienced when cycling on real terrain or provide specialist goal based interval training routines.

The adoption of the "recumbent" position for cycle ergometers has become an increasingly popular design. These systems feature a more traditional seated posture which places the crank arms and pedals of the cycle directly in front of the user. This configuration improves system comfort and allows the user to produce additional force by utilising the seat as a fixed surface to push against. Maximal and sub-maximal cycling in this manner has been found to result in similar cardiovascular responses to traditional upright cycling (Saitoh *et al.*, 2005). Muscle activation patterns and recruitment are also comparable between the two orientations (Hakansson & Hull, 2005).

2.1.1.3 Stepper

Stepper machines utilise the gravitational load of the user to apply additional force to the muscles of the lower body. Modern commercial steppers use a foot platform system to replicate a typical climbing motion. These platforms can be coupled as a pair or may operate independently. Resistance is applied using frictional or pneumatic mechanisms. The stepper system is a non-impact exercise which places high levels of stress upon specific muscle groups, particularly the quadriceps and calves. However, recent developments in these types of machines have resulted in an improvement in muscle recruitment distribution by introducing additional movement planes as shown in Figure 2.3.

Figure 2.3: Operational movement planes offered by state of the art stepper devices.

2.1.1.4 Rower

The in-home market for rowing machines is relatively small due to high purchase costs whilst the commercial gym market is currently dominated by a single manufacturer, Concept 2. A simulated rowing motion is provided by an extendable handle and sliding seat unit. Resistance is applied to the handle as the user pulls in a traditional "oar stroke" movement using friction, air or fluid based systems. Advanced rowing machines allow the level of resistance to be controlled automatically and provide virtual competition and performance feedback for competitive practice and improved concentration. Rowing is widely regarded as the best form of aerobic exercise as the motion requires input from both the upper and lower body. As a non-impact training mode, rowing will not adversely effect joint and bone strength although proper technique is important to avoid excessive strain being placed upon the lower back.

2.1.1.5 Elliptical trainer

Elliptical training machines are becoming an increasingly popular piece of equipment for gym usage (SGMA, 2003). Utilising basic linkage mechanisms, these devices translate normal walking actions into rotary motion. This secondary motion is then used to provide resistance to the user through frictional or magnetic braking systems. The position of the foot platform in relation to the linkage can be adjusted to alter the muscular loading characteristics. Early examples of the elliptical trainer provided resistance exclusively for the lower body although modern systems feature upright linkages which are simultaneously activated by the upper body. The non-impact, controlled resistance features exhibited by these devices are considered as highly desirable and therefore it is not unexpected that such systems are replacing the traditional treadmill in general training environments.

2.1.1.6 Arm ergometer

The arm ergometer is considered as a relatively specialist item of exercise equipment. Originally designed for individuals with limited or no capacity for lower body movement, these systems are fundamentally similar to standard cycle ergometers. A pair of handles are placed on a set of cranks arms which operate in a circular path. Resistance is applied using identical methods as those discussed previously for the cycle ergometer (see section 2.1.1.2). These systems are useful at providing isolated endurance training stimulus for upper body development. However, recent developments have resulted in the combination of arm and cycle ergometers to provide both upper and lower body training facilities as shown in Figure 2.4.

Figure 2.4: Integrated cycle and arm ergometer for simultaneous upper and lower body training.

2.1.1.7 Aerobic equipment summary

Aerobic equipment remains the most popular form of training system in commercial gym environments. The broad training stimuli offered by treadmills provides a time efficient method for improving general fitness and overall health. Although the high impact nature of the running and walking motions supported by treadmills is beneficial for performance athletes, continued exposure to these types of stresses can be detrimental to casual users (Vuori, 2001). Therefore, it appears that the prevalence of non-impact exercise devices is likely to continue to increase. Early versions of these systems focused upon specific body segments although recent developments have expanded the input capabilities to stimulate a wider range of muscle groups. Entertainment facilities and informative feedback systems are essential for aerobic exercise systems where a user may spend up to an hour or more on a single machine (Potteiger, 1994).

2.1.2 Resistance exercise equipment

Anaerobic exercise equipment is designed to provide specific groups of muscles with an artificially high stress input for short durations. Using the overload principle, additional resistance is applied to the muscle which exceeds that experienced during everyday activity. This high intensity stimulus invokes specific adaptations in the muscular, musculoskeletal and neuromuscular systems which improve the nominal force generation characteristics of that anatomical segment.

2.1.2.1 Free weights

Free weights represent one of the simplest, cheapest and most versatile forms of resistance exercise equipment available. "Free weights" is a collective term used to describe equipment such as dumbbells, barbells and other unrestricted weight products where the magnitude of resistance is altered by simply adding additional mass. These systems allow the user undertake both uni-lateral and bi-lateral exercises.

When using correct technique, the unrestrained nature of these weights helps to develop balance, co-ordination and control whilst exercising a broad range of muscle groups. Free weights can be configured for isometric and isotonic exercise but do not provide the capabilities for isokinetic training. These pieces of equipment require a relatively small operating area and also fit a wide range of users. Exercise velocity and acceleration are both determined by user input.

The lack of defined motion control can lead to poor exercise form and muscle damage if incorrect load levels are selected due to inexperience. Insufficient recovery time for the development of supporting systems can also result in a loss of performance. Direct injury may occur due to loss of control through impacts or trapping between the free weights and the user. Weight adjustment can be time consuming when compared to other forms of resistance equipment and free weights have a sociological stigma which associates their use with professional strength and power training athletes only. Resistance is achieved by moving the mass against the action of gravity, hence muscle overload is limited by the effects of the skeletal lever system as discussed in section 1.2.5.

2.1.2.2 Mechanical deformation devices

Mechanical deformation based devices, such as the Bowflex (Nautilus Inc, 2007), utilise the elastic properties exhibited by some materials to produce an inexpensive, easy to use, portable and relatively safe means of resistance training. This equipment allows the user to define the exact exercise movement path and encourages the development of supporting muscular systems. With basic re-configuration, such devices can be used to train a wide range of different muscle groups, require only a small operational area and little maintenance.

However, mechanical deformation based devices are limited by the characteristics of the resistive load that they provide. Assuming that the material is within the elastic region of deformation, the force exerted on the user is directly related to the distance that the device has been extended. Thus, maximum load is applied at the point of maximum movement which may not correspond to the optimised force profile for that joint as shown in Figure 2.5. Careful mechanical design is required to improve the loading characteristics from the basic material force-elongation relationships. The range and resolution of resistance that can be achieved with mechanical deformation based devices is generally much less than other resistance training equipment.

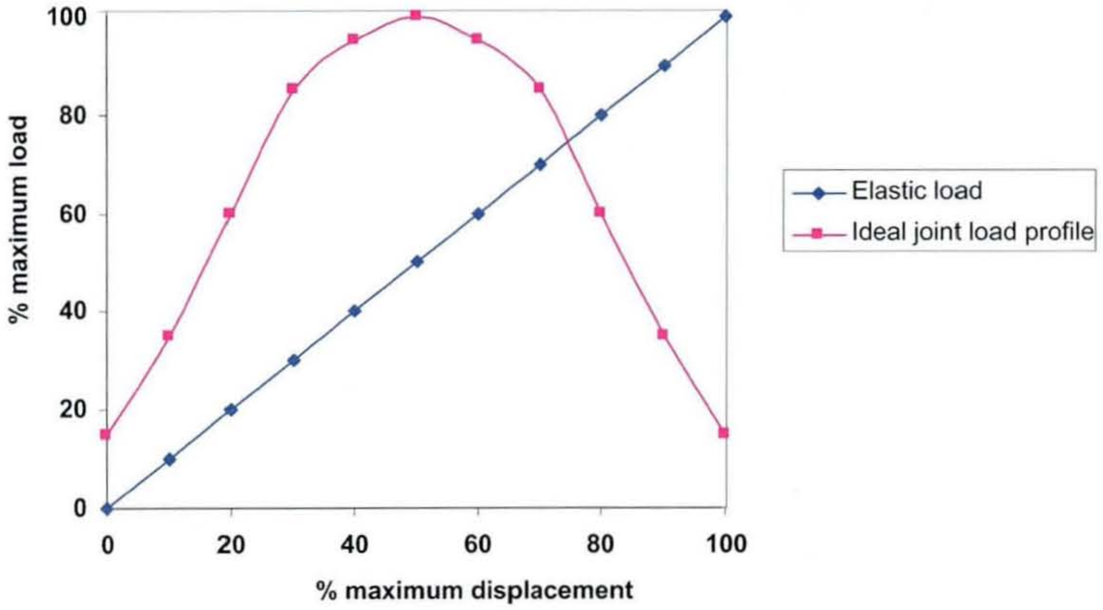


Figure 2.5: Displacement-load characteristics of mechanical deformation resistance devices in relation to a common joint profile.

2.1.2.3 Selectorised devices

The successful introduction of selectorised machines in commercial gyms and favourable user feedback has resulted in the creation of a vast array of different products on the market. These devices fundamentally consist of a simple framework which supports a stack of individual weights. These weights are activated through a series of cables, chains or links that are guided by pulleys and are attached to some form of handle or other input device. This simple lifting arrangement provides similar exercise characteristics to free weights but limits the motion of the user through a system of fixed levers and pivot points. The user applies a force to a particular location on the framework and the resultant motion is restricted by the system to one or two planes. Depending upon the machine configuration, unilateral or bi-lateral exercises can be conducted.

The supporting framework ensures that better form is established in a much shorter time period and reduces the risk of direct and indirect injury, although some trapping and impact hazards do remain. Overall exercise time can be reduced as incremental load increases can be achieved by simply relocating the locking pin to a different weight position. The possibility of over stretching a joint beyond its nominal range of motion can be eliminated by using built in mechanical stops. Restrictions in the motion allow users to isolate specific muscle groups which can be trained independently.

This specificity feature of selectorised devices can also be considered as a disadvantage. The isolation of individual muscle groups is not representative of normal loading conditions and may result in injuries to supporting structures during ordinary activities. Selectorised machines utilise the same gravity based resistance system as free weights. However, recent developments have lead to the introduction of cam based systems which provide a simple load profile as shown in Figure 2.6. These cams provide improved overload capabilities, but are optimised for a small range of the user population. Additional variation in these load profiles can be expected due to the inherent frictional losses of the system and deformation of the connecting elements.

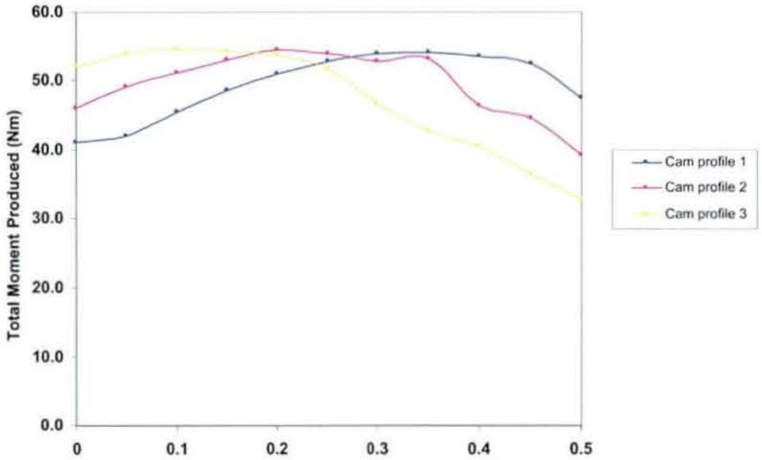


Figure 2.6: A selection of cam profiles utilised by modern isotonic selectorised devices.

From a commercial perspective these devices represent a considerable capital investment and require a relatively larger area for operation. Once installed, movement of these devices is arduous and the number of working parts can lead to relatively high maintenance requirements. Current state of the art devices feature electronic feedback displays and portable performance storage facilities. The system calculates the optimal speed, load and number of repetitions for the user based upon the desired fitness requirements. Particular exercise variables are displayed on the console in real time and stored for subsequent analysis.

Milburn (Milburn *et al.*, 2002) described a device for retrofitting onto an existing selectorised machine to provide a decreasing resistance profile. A tank of water is placed on top of the weight stack which drains into a separate collection area during the exercise, thus there is a net reduction in mass throughout the motion due to the transfer of water. The flow rate is controlled either manually or by computer-control. Daniels (Daniels,2002) describes a system of directly connected cables and pulleys which provide the user with additional freedom of movement. Reconfiguration of these components allows a number of different exercises to be conducted in a similar approach to that of Hoecht (Hoecht & Bohm, 2002). These systems utilise basic selecterised weight stacks and thus can only provide isometric and isotonic exercise modalities but allow quick load changes and encourage the development of supporting muscle groups.

2.1.2.4 Plate-loaded devices

Plate-loaded devices are a combination of free weights and selectorised equipment and exhibit both positive and negative aspects of each of these machines. This apparatus provides the same supportive, motion restrictive framework as utilised in selectorised equipment. Loading is achieved by the addition of basic weight plates which are placed onto simple load bearing members on the equipment and commonly held in place by spring jointed clips or purely through the effect of gravity.

Plate-loaded equipment offers all of the safety benefits of selectorised machines with the ability to vary load at much smaller increments. Generally, these machines are activated through a series of levers and therefore the integration of a cam system is technically more complex. In order to offer some form of variation in profile, weight attachment points are provided at different locations in relation to the central pivot point. A simple model of the different moment effects experienced when relocating the weights about a given pivot is illustrated in Figure 2.7.

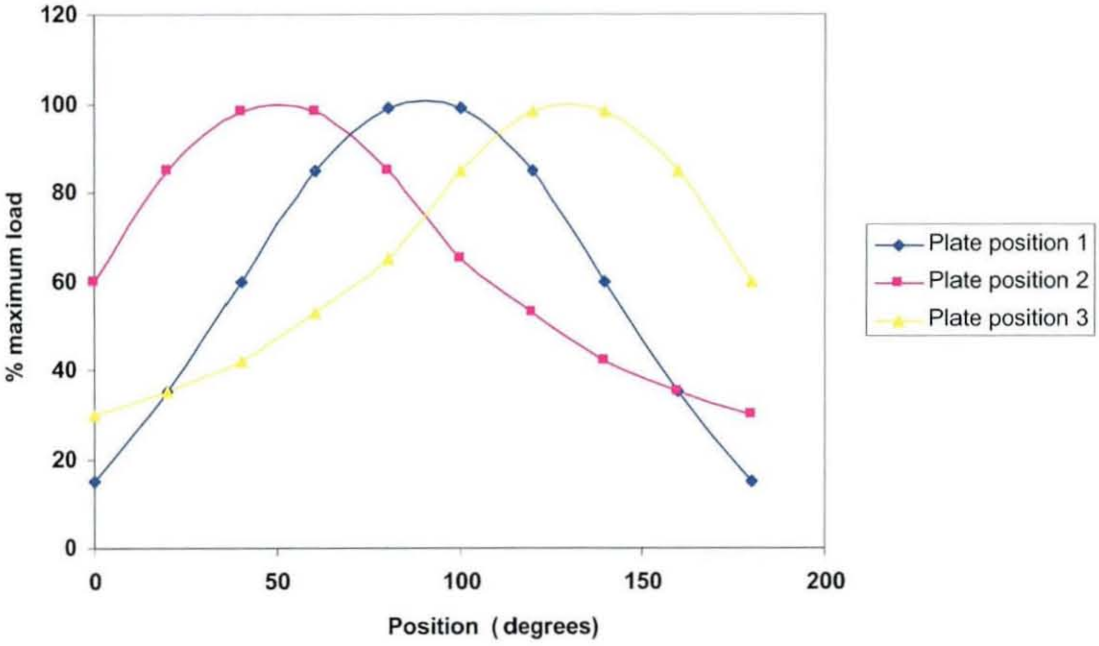


Figure 2.7: Plate location load effects exhibited by modern isotonic plate-loaded devices.

The time required to adjust the weight and the potential for injury during transportation of the weights is increased. Plate loaded machines suffer from a similar, professional's only reputation, as free weights and are generally only ergonomically correct for a narrow range of users. Additional maintenance and space requirements when compared to traditional free weights are also inherent problems.

2.1.2.5 Accommodating resistance machines

State of the art commercial and scientific research equipment provides advanced exercise functionality with progressive rather then incremental load adjustment through electrical, pneumatic and hydraulic resistance methods. Machines such as these are commonly termed dynamometers. Generally, these machines work in a single plane and provide resistance for isolated uni-lateral or bi-lateral motions. Load is increased automatically through a user interface and control system which also provides information on current performance and load settings, as well as offering post exercise analysis options.

These machines can be classified according to the nature of the resistance which can be passive, active or both. Passive devices use mechanical, magnetic, hydraulic, or electrical braking to generate a resistive force against the user. Active devices are capable of producing a force regardless of the user input and thus are able to do work against the applied human effort. This is generally achieved using a computer control based system which operates either an electromechanical servomotor or hydraulic / pneumatic actuator in a closed control loop arrangement.

These devices are capable of providing a range of resistance exercises utilising the major types of muscle action, including isokinetic, isometric and isotonic. This range of exercise modalities is achieved through the control of torque, speed and acceleration throughout the range of motion, although it should be noted that active control may not always be possible. The devices also provide data logging and feedback facilities which are used by medical and academic institutes in order to monitor and record the performance of specific test subjects. The wide range of test modalities, resolution and analysis facilities offered by these devices are highly desirable features for high performance athletic training and testing together with injury and rehabilitation assessment.

The main commercial disadvantages of the devices are the prohibitively high costs (e.g. £40,000), complexity and time implications of correct usage, operational space requirements and reported unnatural training sensations (Perrin, 1993). This means their use is restricted largely to the medical, academic and professional sports domains. The specifications of the main devices currently available are summarised in Table 2.1.

Device	Resistance type	Maximum isometric torque (Nm)	Maximum isotonic torque (Nm)	Isokinetic concentric		Isokinetic eccentric	
				Maximum torque (Nm)	Speed (°sec^{-1})	Maximum torque (Nm)	Speed (°sec^{-1})
CSMI/ Cybex *NORM*	Electro-mechanical	678	406	678	5-500	406	5-300
ISOCOM	Electro-mechanical	500	500	500	1-500	1-500	1-500
LIDO	Electro-mechanical	610	610	610	0-400	610	0-240
ISOMED	Electro-mechanical	500	500	500	0-450	500	0-200
Ariel *ACES*	Hydraulic	Approx. 1000	Approx. 1000	Approx. 1000	0-1000	Approx. 1000	0-1000
Biodex	Electro-mechanical	420	420	680	0.25-500	680	0.25-300

Table 2.1: Technical specifications of existing isokinetic dynamometer equipment.

A review of international patents and research publications identified a number of different accommodating resistance systems which could provide a proportion of the functional exercise modes which were discussed in Chapter 1. Smith (Smith, 1998) proposed a device for exercise, rehabilitation, and testing which outlined the underlying principles used in modern dynamometers. The user is connected to the output shaft of a dynamometer which is capable of rotating about its horizontal and vertical axis. Rotational movements are transmitted through a cycloidal speed reducer to an activation arm which the user exercises against. A similar apparatus was described by Boyd (Boyd *et al.*, 1987) which utilised a closed loop servo circuit with speed and velocity feedback for the control of a simple servo motor.

Anjanappa (Anjanappa & Miller, 1996) describes an exercise machine using a constant torque, variable speed reversible motor, a temperature controlled magnetic particle clutch and a gear reducer. Similar devices have been described by Casler (Casler & Abelbeck, 2002), Krukowski (Krukowski, 1988) and Houston (Houston & Houston, 1999). An affordable electromechanical device for isokinetic testing has been described by Jacques (Jacques *et al.*, 2001). The proposed equipment uses a simple motor and controller adapted to maintain a constant output shaft speed. Specific linkages transmit force between the exercise arm and the output shaft through a system of unidirectional clutches.

It is clear from the analysis of current electro-mechanical systems that previous solutions have favoured the use of DC servo motors as the primary drive mechanism. These motors are generally arranged in series with some form of clutch mechanism to provide the necessary functionality and level of torque control. The output from the clutch is subsequently passed through a reduction gearbox, the output of which the user will work directly against. This generalised drive arrangement is shown in Figure 2.8.

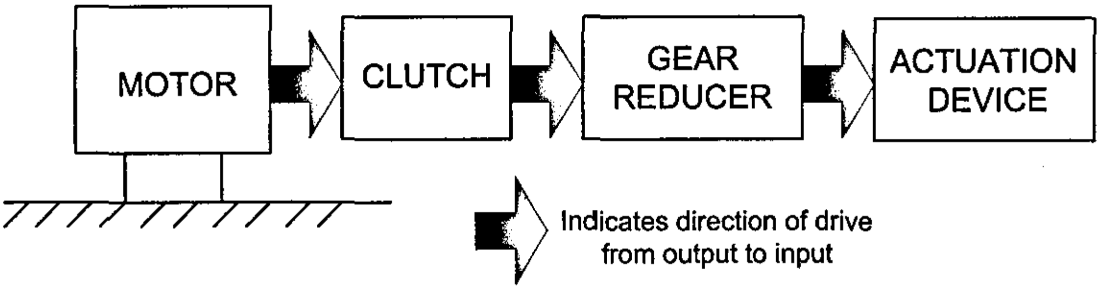


Figure 2.8: Block diagram of the general drive arrangements exhibited by previous solutions.

Paterson (Paterson & DuPont, 1989) describes a machine that employs a fluid actuator to provide resistance for exercising using the three main exercise categories and both concentric and eccentric actions. Fluid pressure variation is achieved through direct control of a servo pump using an integrated microprocessor and position and pressure feedback signals. A similar device is described by Petrofsky (Petrofsky & Gruesbeck, 2000) which utilises a two stage pilot operated solenoid valve to regulate flow and provides similar functional capabilities.

Cook (Cook, 1989) proposed a closed system pneumatic exerciser, which includes a double acting pneumatic cylinder. An external line connects the chambers formed within the pneumatic cylinder on either side of an enclosed piston. A handle or other engaging device is attached to a shaft connected to the piston to enable a user to push and pull the piston against the air pressure developed in the corresponding chamber.

The device proposed by Daniels (Daniels, 2000) creates a variable resistive force using variable viscosity fluids. Electro-rheological fluid is used which increases its viscosity when an electric potential is applied. Thus, by varying the electrical properties of the system, variable resistance is created against objects passing through the fluid. Similar systems developed by Kikuchi (Kikuchi & Furusho, 2003) and Nikitczuk (Nikitczuk *et al.*, 2006) provide isometric and isotonic exercise modes, but are also capable of providing concentric isokinetic movement. This is achieved using a high speed control system to alter the applied resistance in relation to the input speed in pseudo real time.

A system developed at Loughborough University (Yang *et al.*, 2006) utilises a series of magnetic particle brakes arranged in a novel mechanical structure to provide passive isotonic resistance in three degrees of freedom. This system provides a wide range of resistance capabilities but is restricted by the inertial effects of the actuator mechanisms. Dong (Dong *et al.*, 2006) has utilised magneto-rheological fluids in a linear damper arrangement to create a passive device for knee rehabilitation. The maximum resistive torque of these rehabilitation systems is relatively low compared to that of commercial isokinetic dynamometers. Thus these systems are suitable for rehabilitation applications but do not provide sufficient capabilities for training exercise conditioned individuals.

To date, limited research has been conducted on the suitability of the use of cables on with accommodating exercise machines to provide variable, unrestricted resistance movements. Automatic control of the load for optimised training would require some form of three dimensional tracking system in order to determine the exact position and orientation of the limb being exercised. Work conducted by Brown (Brown, 2001) suggested that constant velocity universal joints could be incorporated into uni-axial exercise devices to create multi-axial movements. The rigidity of these joints in specific planes allow eccentric exercises to be conducted and if coupled to a accommodating resistance device should produce all the predefined exercise modalities with improved freedom of movement.

2.1.2.6 Resistance equipment summary

The popularity of free weights and incremental loading machines in in-home and commercial gym applications can be attributed to their ease of use and robustness. These systems offer isometric and isotonic functionality with user controlled velocity and acceleration but fail to provide suitable facilities for creating resistance profiles for all users. Recent technological developments have enhanced exercise instruction, feedback and entertainment, but have failed to address the basic physiological problems associated with this form of exercise equipment.

A device that could provide the same exercise functionality as existing accommodating resistance devices, but at significantly lower cost would therefore have a strong competitive advantage in the marketplace and would greatly enhance general training programmes. Such a device could include rotational elements to incorporate improved freedom of motion and thus aid in the development of supportive structures and co-ordination as experienced with free weights. In order to appeal to inexperienced users, the system must be intuitive and provide additional injury prevention mechanisms to reduce safety concerns and apprehension associated with resistance exercise.

2.2 Quantitative system requirements

The information extracted from the review of existing equipment and general user requirements suggested that there was a definite opportunity for the development of a multi-function modular exercise system that could provide both aerobic and anaerobic training stimulus from a single unit. The fundamental physiological and biomechanical principles of these exercise routines have been discussed in Chapter 1. However, it is important to consider these requirements from a mechanical / electro-mechanical perspective to ensure that the proposed resistance system provides the necessary range of capabilities. For each of the exercise categories identified, there is a specific set of velocities, loads, accelerations, decelerations and ranges of movement which are associated with these actions. It is important to characterise these parameters such that a balanced and informed selection process can be undertaken.

2.2.1 Aerobic equipment operational data

2.2.1.1 Treadmill

The operational parameters for treadmills differ slightly to the other aerobic equipment as there is no requirement for variable resistance. The system must simply provide a sufficient level of force to maintain the required speed during the foot contact periods. The linear speed of the treadmill surface varies between 0-25 kph. Given a minimum driven roller diameter, D_{rol}, of approximately 70 mm and direct connection to the motor, motor speed, V_{mot}, can be calculated.

$$\text{Roller circumference, } C_{rol} = \pi \times D_{rol} = \pi \times 0.07 = 0.220m \qquad (2.1)$$

$$\therefore V_{mot} = \frac{\left(\frac{25000}{60}\right)}{0.220} = 1894.702RPM \qquad (2.2)$$

The power produced by a treadmill is subdivided into two categories; peak power and continuous power. Peak power, P_{max}, is the instantaneous maximum output that can be achieved with the system (maximum 7.5 HP) whilst continuous power is the nominal operating level that can be sustained for extended periods of time without exceeding performance limits (maximum 3.5 HP). The maximum torque of the motor, τ_{mot}, can be calculated for the instantaneous power rating.

$$P_{\max} = F \times V \Rightarrow F = \frac{P_{\max}}{V} = \frac{5592.749W}{6.944ms^{-1}} = 805.407N \tag{2.3}$$

$$\tau_{mot} = F \times \frac{D_{rol}}{2} = 805.407 \times \frac{0.07}{2} = 28.190Nm \tag{2.4}$$

2.2.1.2 Cycle ergometer

Cycling performance is often expressed in terms of power. World class track cycling athletes have been shown to produce in excess of 1600 W of power at 150 rpm (Dorel *et al.*, 2005). During testing, these highly specialist sprint cyclists were capable of producing cadences around 280 rpm and instantaneous maximal torque inputs of 270 Nm. It should be noted that commercial exercise cycles are generally capable of providing 600 W at approximately 100 rpm (Tunturi, 2004).

2.2.1.3 Stepper

The linkage mechanisms and transfer systems used in stepper machines vary according to the primary resistance source. Resistance is directly related to the mass of the operator as the active elements of the system also provide the reactionary force for supporting the overall body weight. Commercial stepper devices have a maximum weight limit of 160 kg with a step displacement of approximately 0.4 m. Velocity is directly related to the applied resistance with a maximal repetition rate of 13 floors per minute where a "floor" represents a full movement of the foot plate from the raised position to the lowered position. For the purpose of determining a set of basic operational parameters it has been assumed that the motion occurs in the vertical plane, velocity is constant and the full mass is cyclically applied to each platform. The linear resistance force, F_{max}, and power, P_{max}, applied to a single platform can be calculated as follows:

$$F_{\max} = m \times a = 160 \times 9.81 = 1569.6N \tag{2.5}$$

$$V = \left(\frac{13}{60}\right) \times (0.4 \times 2) = 0.173ms^{-1} \tag{2.6}$$

$$P_{\max} = F_{\max} \times V = 1569.6 \times 0.173 = 272.064W \tag{2.7}$$

2.2.1.4 Rowing machine

Rowing machines provide an overall training load by applying a resistance through the system handle which is pulled by the user using muscle groups of both the lower and upper body. Previous research into rowing performance has shown that world class rowers produce a maximum extension velocity, V_{pull}, during the drive phase of the stroke, of approximately 3.8 ms^{-1}. The maximum instantaneous force, F_{max}, produced was found to be 1350 N and peak power, P_{max}, 3230 W. Given that the radius of rotation, r_{fly}, of the flywheel mechanism is 0.2m, the rotational speed of the flywheel, V_{fly}, and resultant torque about the centre of rotation, τ_{fly}, can be determined.

$$\text{Flywheel circumference, } C_{fly} = \pi \times (2 \times r_{fly}) = \pi \times 0.4 = 1.257m \tag{2.8}$$

$$\therefore V_{fly} = \frac{(3.8 \times 60)}{1.257} = 181.437RPM \tag{2.9}$$

$$\tau_{fly} = F_{\max} \times r_{fly} = 1350 \times 0.2 = 270Nm \tag{2.10}$$

2.2.1.5 Elliptical trainer

Elliptical trainers differ to treadmills by providing a passive rather then active input to the user. Linear motion is provided by a linkage system which is attached to a cylindrical resistance system. The resulting motion follows a traditional cam profile such that vertical position and horizontal displacement vary proportionally. The speed of movement can be varied to equate to a relative running speed of 0-25 kph. The basic linkage structure of an elliptical trainer and the free body diagram used to calculate the dynamic load placed upon the resistance system is illustrated in Figure 2.9. Assuming that the maximum force applied to the system is due to the mass of the user, the resistive torque, τ_{max}, can be calculated using diagram 1. Resolving about point C;

$$F_{\max} \times L_Y = Mg \times L_X \tag{2.11}$$

$$F_{\max} \times (Cos12 \times 1.25) = (160 \times 9.81) \times (Cos12 \times 0.5) \tag{2.12}$$

$$\therefore F_{\max} = \frac{767.650}{1.223} = 627.840N \tag{2.13}$$

$$\tau_{\max} = F_{\max} \times r_{AB} = 627.840 \times 0.25 = 156.960Nm \tag{2.14}$$

The rotational speed of the resistance system can be determined assuming that the maximum horizontal speed occurs when linkage AB is a bottom dead centre as shown in diagram 2, Figure 2.9. Thus;

$$\text{Resistance system circumference}, C = \pi \times (2 \times r) = \pi \times 0.5 = 1.571m \tag{2.15}$$

$$\therefore V_{fly} = \frac{(6.94 \times 60)}{1.571} = 265.088RPM \tag{2.16}$$

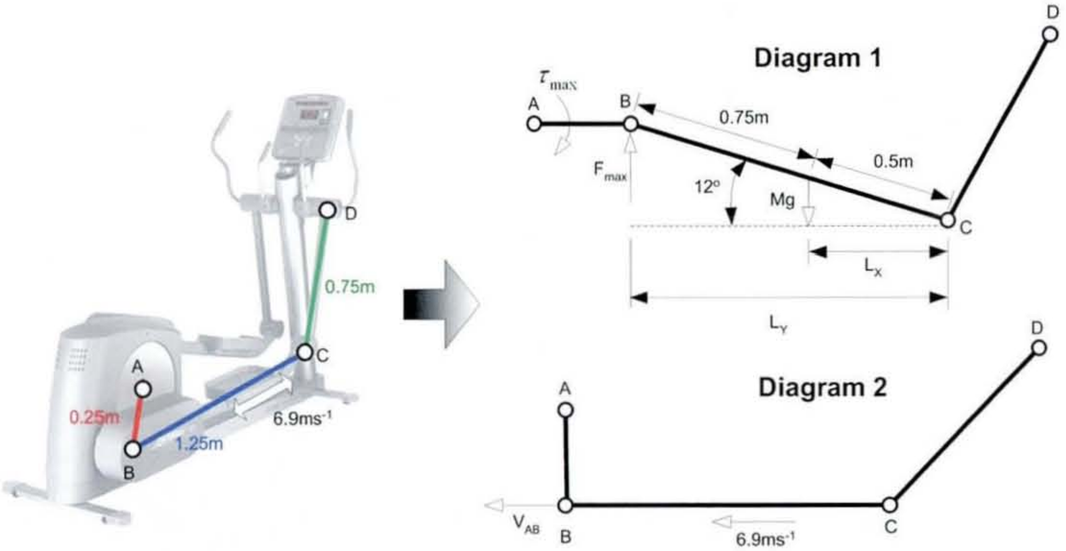


Figure 2.9: Elliptical trainer linkage mechanics and associated free body diagrams.

2.2.1.6 Arm ergometer

Arm ergometers utilise similar resistance mechanisms to those identified for traditional cycle ergometers. The maximum power, P_{max}, that commercial systems can produce is 1000 W with load independent speed capabilities of 30-150 rpm. Using the velocity and torque relationship established by Vanderthommen (Vanderthommen *et al.*, 1997), maximum torque will be produced at minimum speed, therefore at 30 rpm the theoretical torque produced will be 133 Nm for an average male user.

2.2.2 Resistance equipment operational data

In order to determine the operational parameters and reconfiguration requirements for anaerobic training, it was necessary to define the precise number of different exercises that would be provided. The basic muscle group categories that are used during typical anaerobic training sessions and the most popular exercise motions used to stimulate each group are defined in Table 2.2. An optimal solution would produce all of the desired exercise functionality with minimal hardware reconfiguration.

Although the primary motion that has been associated with a number of these exercises is defined as linear, it is possible to create a suitable movement using the shallow arcuate paths created by particular linkage and pivot systems. Such systems generally require lengthy and complex mechanisms which are supported by bulky framework structures. Therefore in order to maintain a relatively compact operating volume, it was decided that the modular exercise system would focus upon those exercises which require rotational movements only. A brief review of human performance data was conducted to determine the exercise or exercises which produce the maximum force and velocity characteristics. The experimental results from leg extension and flexion testing were consistently shown to produce the highest output values when compared to the other exercises identified. Therefore, the attributes of this lower body muscle group were used as the limiting values for specifying the anaerobic training requirements.

Anatomical category	Common exercise	Nature of motion
Arms	Bicep curl	Rotational - reciprocating
	Tricep curl	Rotational - reciprocating
Legs	Leg flexion (hamstring)	Rotational - reciprocating
	Leg extension (quads)	Rotational - reciprocating
	Leg press	Linear - reciprocating
	Leg abductor	Rotational - reciprocating
	Leg adductor	Rotational - reciprocating
Shoulders	Shoulder press	Linear - reciprocating
Chest	Chest press	Linear - reciprocating
	Cross-overs	Rotational - reciprocating
Abdomen	Ab curl	Rotational - reciprocating
Back	Lat pulldown	Linear - reciprocating
	Seated row	Linear - reciprocating
	Lower back extension	Rotational - reciprocating

Table 2.2: Summary of the potential exercise routines that may be provided by the modular exercise system.

The following data represent the practical and recommended performance limits when conducting strict unilateral leg extension exercises. Torque, velocity and acceleration values have been calculated in respect to the axis of rotation of the knee joint. In general, it is recommended that the axis of rotation of any exercise system that utilises a rotary drive must be aligned with that of the primary joint activated.

Therefore the following information can be used directly in the specification of a rotary resistance mechanism but must be adapted for other arrangements.

2.2.2.1 Isometric

During an isometric exercise the user exerts a force against a stationary object. When operating in an isometric mode, there must be no movement in the actuator or resistance system and therefore both acceleration and velocity are always zero. The exact method employed to achieve this state will depend upon the particular resistance approach, but critical consideration should be given to the requirements and effects of holding each system for prolonged periods in a static condition. Maximum isometric performance data for knee extension is shown in Table 2.3.

Exercise parameter	Value
Stationary torque	250 Nm
Exercise duration	10 s
Number of repetitions	3
Rest period between sets	30 s
Number of repetition sets	15

Table 2.3: Key operational parameters for isometric exercises.

2.2.2.2 Isokinetic

Isokinetic exercise can be distinguished from the other training modes by the constant velocity which is maintained throughout the range of motion. In this mode, velocity, acceleration and deceleration are controlled by the system. Constant velocity must be maintained regardless of the magnitude and direction of the input torque applied by the user. The acceleration and deceleration profiles implemented by existing rehabilitation and exercise systems are varied and have received considerable academic research (Osternig, 1975; Sepega, 1982; Winter et al., 1981). The particular acceleration and deceleration procedures utilised by the system have an important effect upon the quality and accuracy of any measurements taken during the exercise. Research has identified a number of undesirable data anomalies which are caused by the interactions between the system and the user during the velocity change stages. A number of alternative solutions have been proposed to reduce or eliminate these oscillations such as isometric preloading and data windowing.

For the purpose of selecting a basic resistance system it is only necessary to consider the magnitude of the velocity changes and the level of control available. The incremental speed increases shown in Table 2.4 provide a practical guide to acceleration values based upon position change (Segar *at al.*, 1988):

Displacement (degrees)	**Speed increase (degrees/s)**
0 – 5	0 – 100
5 – 10	100 – 200
10 – 15	200 – 300
15 – 20	300 – 400

Table 2.4: Proposed velocity change based on position.

Assuming that acceleration is approximately linear, the speed increase from initial velocity, ω_o, to the next velocity step, ω, over each angular displacement, θ, is 100 (°/s). Therefore, acceleration, α, can be found using the following equation:

$$\omega^2 = \omega_o^{\ 2} + 2\alpha\theta \tag{2.17}$$

$$\therefore \alpha = \frac{\omega_o^{\ 2} - \omega^2}{2\theta} = \frac{400^2 - 300^2}{2 \times 5} = 7000^o \sec^{-2} \tag{2.18}$$

It has been recommended that a similar deceleration relationship is utilised once the desired range of motion has been completed. Unacceptable inertial characteristics and other torque effects are produced if these incremental speed changes are conducted over shorter time periods. Increasing the relative time periods would eventually result in a situation where the system will never reach a state of constant velocity or the duration is so short that any information collected is completely ambiguous. Maximum isokinetic experimental performance data is shown in Table 2.5.

Exercise parameter	Value
Torque	350 Nm
Velocity	500 deg/s
Acceleration/Deceleration	7000 deg/s^{-2}
Exercise duration	4 s
Number of repetitions	10
Rest period between sets	30 s
Number of repetition sets	3

Table 2.5: Key operational parameters for isokinetic exercises.

2.2.2.3 Isotonic

Isotonic exercises are characterised by their constant load conditions. In this mode of operation, the system is required to maintain a set output torque regardless of user input. The movement velocity and accelerations are determined by the user input. During a true isotonic exercise the force applied to the muscle group will remain perfectly constant throughout the exercise as shown in Figure 2.10.

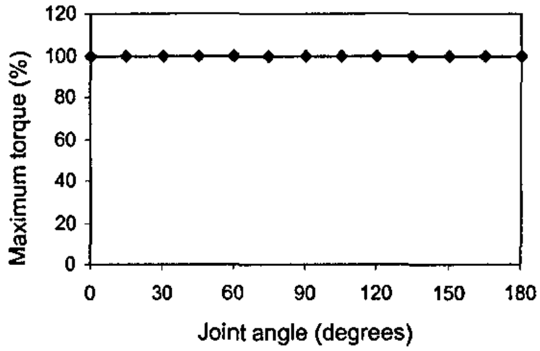


Figure 2.10: The torque and position relationship exhibited during a true isotonic exercise.

The majority of equipment currently used for isotonic exercise does not provide this uniform load characteristic. Instead the resultant force experienced when using this apparatus varies according to position. The popularity of these systems and their ability to replicate actual loading scenarios means that the specific operational features of these loading conditions must be considered in parallel with the basic isotonic exercise requirements as shown in Table 2.6.

Exercise parameter	Value
Torque	175 Nm
Velocity	960 deg/s
Exercise duration	10 s
Number of repetitions	10
Rest period between sets	30 s
Number of repetition sets	3

Table 2.6: Key operational parameters for isotonic exercises.

2.2.2.4 Free weight replication

Free weights are the simplest and most widely used piece of isotonic training equipment. The overall weight selected by the user determines the magnitude of the applied load, but it is the geometry of the limbs engaged during the exercise that will determine the resultant torque profile. Due to the popularity of this type of equipment and the general familiarity that has developed with the "feel" of the movement, it is important that the proposed system is capable of reproducing the torque characteristics associated with free weight exercises.

When replicating human biomechanical rotational movements it is crucial that the actuators axis of rotation is centred about that of the major active joint. Therefore, in order to produced a realistic representation of the resultant torque, the modular exercise system must be capable of producing a load-position relationship such as that shown in the first data series in Figure 2.11.

This relationship represents the torque required to move the weight at a constant velocity. Initial acceleration of the weight at the beginning of the movement and subsequent deceleration at the end has been omitted. In order to improve the realism of any free weight simulation mode, it is important that these inertial effects are incorporated into the system. There is limited research which presents data regarding the angular accelerations that occur during isotonic exercises. For the purpose of this example, maximum acceleration values have been extract from a set of experimental data points used to illustrate velocity change over a range of motion of 120 degrees (Seger et al., 1988). A linear acceleration profile was used between each velocity value. The second data series in Figure 2.11 shows how the inertial effects of the load alter the torque / position relationship during a contraction at maximum velocity.

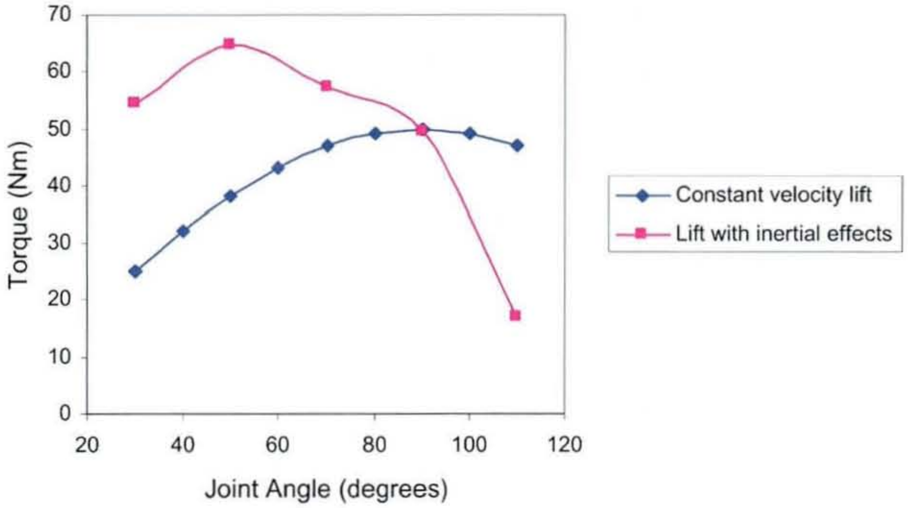


Figure 2.11: The theoretical torque and position relationships experienced during a free weight exercise including the inertial effects of the load.

If an accurate free weight simulation is to be achieved, the resistance system must be able to vary the applied torque to produce a range of effects similar to those identified. For true inertial loading, the system must be capable of monitoring the input acceleration at sufficiently high sample rates in order to make the appropriate torque adjustments during the movement. The total time taken to complete a full repetition during maximum effort was calculated to be approximately 0.7 seconds. Therefore, in order to alter the applied torque in respect to each degree travelled, an optimum sample rate of 170 Hz would be desirable. The inherent inertial effects of the system must also be compensated for when implementing any isotonic exercise mode, including free weights.

2.2.2.5 Selectorised and plate-loaded device replication

The torque characteristics associated with selectorised and plate-loaded devices were discussed briefly in the section 2.1.2. The key profile characteristics that can be achieved using these items of equipment were investigated to ensure that the modular exercise system was capable of replicating the operation of these industry standard devices. The majority of modern selectorised machines utilise some form of curved cam or asymmetric loading arrangement to give a variable torque-position relationship. On the system shown in Figure 2.12 the cam mechanism can be identified and is shown together with a series of simplified images which represent the operation of such a system during a lifting action.

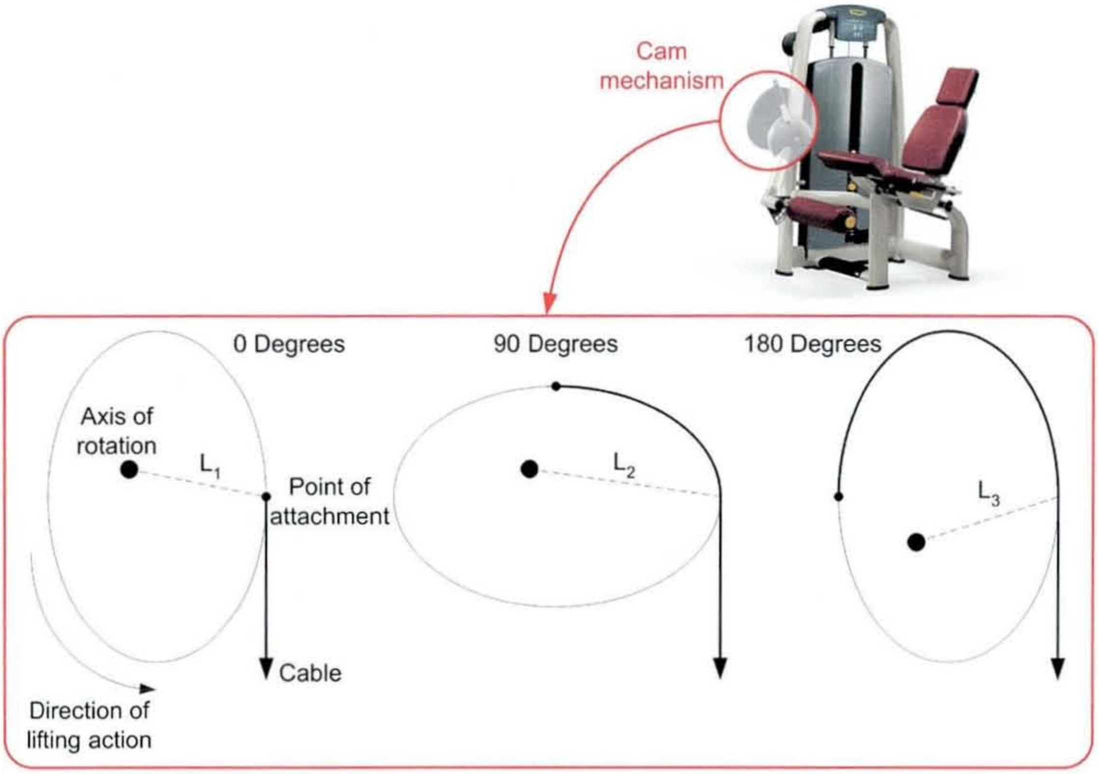


Figure 2.12: Operational characteristics of the cam mechanism utilised by many commercial exercise machines.

The individual weights, m, are attached to the cam via a cable and the cam is activated by the user through some form of mechanical connection. The distance between the axis of rotation and the line of action of the cable, d, alters as the cam rotates with the lifting action of the user (i.e. $L_1<L_2>L_3$). Assuming there is no net moment of the machine arm or the counterweight, the cable is considered as non-elastic, there are no frictional losses and acceleration due to gravity, g, is constant, the resultant torque, τ, can be calculated.

$$\tau = m \times g \times d \tag{2.19}$$

The first data series in Figure 2.13 shows the theoretical torque profile when using a selectorised machine at a load level equal to that used in Figure 2.10. It is clear from these data that the magnitude of the torque experienced by the user is considerably less then that determined for a free weight of the same load although additional loading would be expected due to frictional losses and unbalanced system component masses. The relationship between torque and position has been found to be relatively uniform when compared to that of a standard free weight exercise. These data represent the torque required to move the desired weight at constant velocity and do not consider any acceleration / deceleration requirements. Assuming that the inertia of the weights act as a point mass located at the edge of the cam the resulting loading profile is shown in the second data series in Figure 2.13.

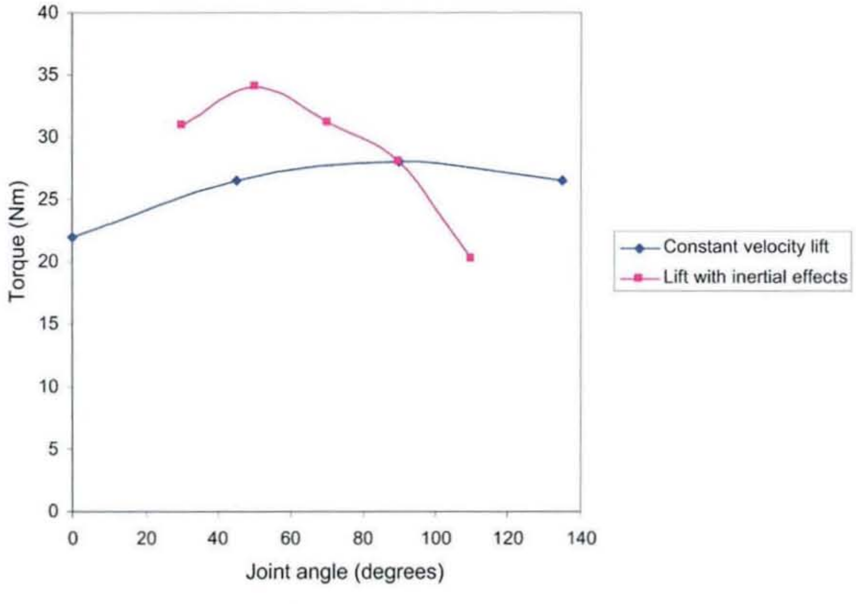


Figure 2.13: The theoretical torque and position relationships for a selectorised device including the inertial effects of the weights.

2.2.2.6 Individualised user strength curves

Although free weights and weights machines continue to be an integral part of both commercial and personal gyms, the emergence of new technologies and monitoring systems has expanded the range of permissible loading conditions. Using isokinetic test data it is possible to identify particular force characteristics for each muscle group. This information can then be used to create a unique isotonic load profile. This customised profile will ensure that the user exercises at an optimal level which can be adjusted to give a constant overload throughout the range of motion. Specific features can be incorporated into the profile to account for injury, weakness or intensive sports training.

It is envisioned that any torque-position relationship such as that shown in Figure 2.14 could be created using the modular exercise system. If complex torque curves such as these are to be implemented, it is essential that the resistance system can achieve a broad spectrum of torque and position relationships. The system must be able to apply rapid but controlled torque changes regardless of the accelerations and velocities applied by the user.

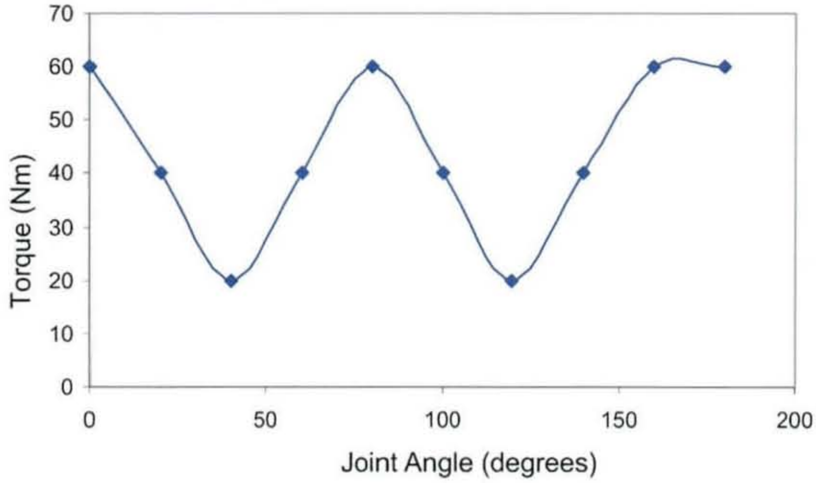


Figure 2.14: Speculative example of a customised isotonic load profile.

2.2.2.7 Variokinetic

The principles of the variokinetic mode have been discussed in the literature review (see Chapter 1). In this particular mode, the resistance system will react to both the speed of the exercise and the torque applied to the user as shown in Figure 2.15. With sufficient experimental data, the system will replicate the specific loads and velocities encountered during sporting activities, work related actions or other quantifiable motion.

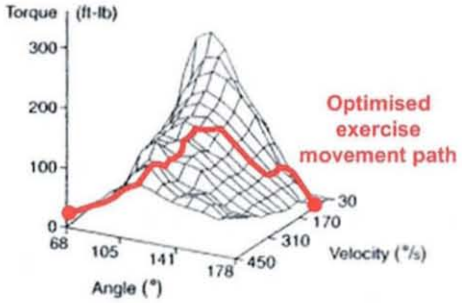


Figure 2.15: Example of a variokinetic movement path based upon data from the three dimensional performance map.

In order to produce a true "variokinetic" mode the system must be capable of controlling torque and velocity independently. As variokinetic exercise is a completely original experimental mode, there is currently no data available to specify the operational parameters of the proposed approach. Therefore, for the purpose of defining a set of quantitative requirements, it has been assumed that the system must satisfy the limiting isotonic and isokinetic factors simultaneously.

2.3 General design requirements

Some form of mechanical assembly is required to transfer the training stimuli quantified in the previous section from the resistance source to an exercise specific actuator. This actuator is the physical interface between the user and the system. Additional mechanical structures which support and protect the resistance system and the associated hardware must be developed. Details of user positioning, support and safety features and their integration with the main framework were also required. These general design requirements have been covered in detail in the design specification (see appendix A) and have been summarised here.

2.3.1 Physical characteristics

The maximum operational envelope stated in the specification is represented by a two metre cube. The structure was configured to reduce the space requirements as much as possible. The overall system dimensions must not compromise unit stability or unduly effect hardware operation. Materials selection and operational mechanisms must conform to the appropriate standards and should be arranged to minimise internal performance losses without compromising durability. Coaxial alignment of the axis of rotation of the actuator and the anatomical joint to be exercised is essential and the resulting movement must be capable of exceeding the user's range of motion. The positioning and operational mechanisms must be intuitive to use and easy to set-up. Potential hazards or harmful areas must be enclosed as defined in the appropriate standards and careful consideration should be given to the ergonomics of the human / machine interfaces.

2.3.2 Aesthetics

The external appearance and finish of the system is not critical for the preliminary solution although some form of suitable cover will be required for demonstration purposes. Appropriate safety information must be displayed clearly and colour coding of parts for ease of recognition could be beneficial.

2.3.3 Legislation

Any exercise device such as that developed during this research which involves some form of direct interaction with human operators must adhere to a strict set of product guidelines. These standards specify essential requirements which must be fulfilled the system. The provision of both aerobic and anaerobic exercise modes implies that the system under development must comply to British Standards BS EN 957-1:2005 (British Standard, 2005) and BS EN 957-2:2003 (British Standard, 2003a) which relate to general fitness equipment design. Consideration must also be given to British Standards BS EN 957-5:1997 (British Standard, 1997), BS EN 957-6:2001 (British Standard, 2001), BS EN 957-7:1999 (British Standard, 1999), BS EN 957-8:1998 (British Standard, 1998), and BS EN 957-9:2003 (British Standard, 2003b) which specifically relate to the operation of pedal crank equipment, treadmills, rowing machines, steppers and elliptical trainers respectively.

2.4 Summary

Current training devices and equipment for aerobic and anaerobic exercise were identified together with an explanation of the basic operational characteristics of each system. A detailed quantitative analysis was conducted to determine the maximum resistance parameters of each device in order to determine the optimal performance requirements for the modular exercise system. The data indicated that the developmental resistance source must provide aerobic exercise capabilities that equate to a resistive torque of 270 Nm and maximum speed of 1900 rpm. In order to satisfy anaerobic exercise requirements, the system must be able to withstand a static load of 250 Nm for ten seconds without any adverse effects, maintain a constant speed of 500 deg/s under a maximum load of 350 Nm, produce a range of resistive torque profiles up to a maximum value of 175 Nm at speeds not exceeding 960 deg/s and offer independent control of torque and velocity.

A design specification was produced to outline the precise requirements of the device to allow accurate and efficient design and selection of mechanical, electrical and software systems. This specification uses the quantitative resistance system requirements and other information collected during the background research to produce an unambiguous document listing the essential features of the proposed exercise system. The mechanical system must be capable of supporting the internal components and resist the reaction forces created by the transmission. User safety and comfort is a primary design consideration during the development process.

Chapter 3

Formalised exercise systems modelling approach

3.0 Introduction

The need to capture, test and implement system based knowledge is an important aspect in a broad range of academic and industrial applications. In order to plan, develop and understand the operation of a system, whether that be a particular piece of software or a production facility for instance, it is essential that any information is recorded in a simple and effective manner which is easy to interpret. A great deal of research has been focused on the development of formalised methods for representing new and existing systems. This research has lead to the creation of a large number of different application specific solutions. The aim of these methods has been to provide a means for visualising system information in a textual or graphical format which is organised within a defined structure.

The arrangement of system information in this from has become known as modelling. System modelling techniques are used to represent real life processes that are composed of a series of inputs which are used by activities and subsequently transformed into outputs. Models are created using specific methodologies and modelling constructs that are organised within an overall framework. This framework defines the precise modelling principles for a particular technique and may consist of a number of architectures. Architectures are based around a set of related modelling elements which together have a definite focus (Vernadat, 1996). Careful decomposition of the system in this manner is essential to avoid excessive complexity. Different architectures and their associated methodologies / modelling constructs will be utilised depending upon the level of generality of the system under investigation and the exact purpose of the model.

The various modelling frameworks which have been developed are designed to introduce commonality between the models produced. Information captured which is found to be used frequently can be stored in a standardised format and re-used, thereby reducing the time and cost implications of producing such models (Monfared, 1997). An effective system model will allow analysis of the information to be undertaken and may include some form of process simulation. Tests may be conducted during system development as a means of evaluating alternative solutions prior to implementation and also during operation in order to monitor and evaluate performance (Vernadat, 1996).

3.1 Characteristics of a computer integrated exercise system

The purpose of this study was to identify, analyse and implement an effective system modelling technique for illustrating the operational aspects of a computer integrated exercise system such as that shown in Figure 3.1. The system depicted in this block diagram identifies a set of elements which are not intended to be exhaustive but characterises the fundamental structure of a basic exercise system.

The proposed system definition consists of six basic components: the user interface, a processor, an information database, a resistance method and control system, safety systems and the physical actuator. The user interface represents the potential communication paths between the user and the system. Data regarding the exercise and any additional information that may need to be stored permanently is uploaded into the information database. The resistance method and control system represents the equipment used to provide a training load and the methods for controlling that equipment. The processor receives, processes and transmits signals from the user interface, resistance method and control systems and the information database. Any passive or active mechanisms which protect the user or equipment from damage are symbolized by the safety systems construct. The physical actuator is the link between the users input and the resistance method.

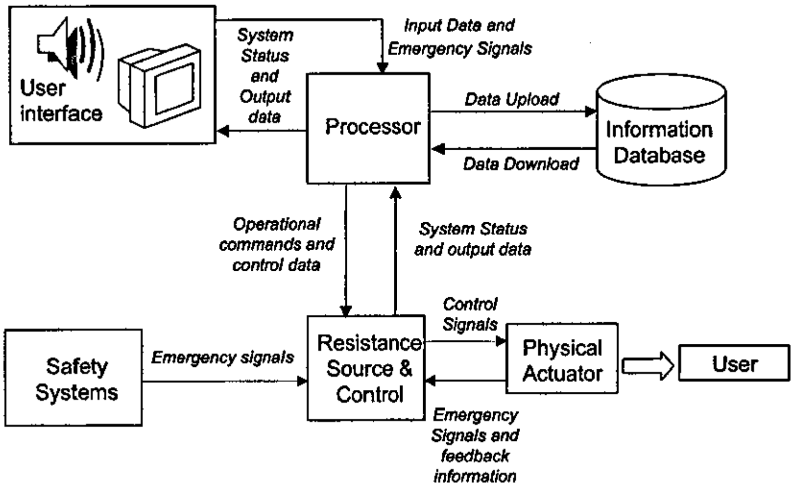


Figure 3.1: Fundamental components of a computer integrated exercise system.

The operational requirements of an exercise system such as that proposed here are complex and therefore it is important that a detailed plan is established before development begins in order to produce an effective and efficient solution. The importance of system models as a planning and reference resource during the product development process is shown in Figure 3.2. The potential range of user input into the model should result in well defined specification which meets all of the requirements and ensures each aspect of the system is correctly integrated and developed, thereby greatly enhancing the chances of successful system implementation.

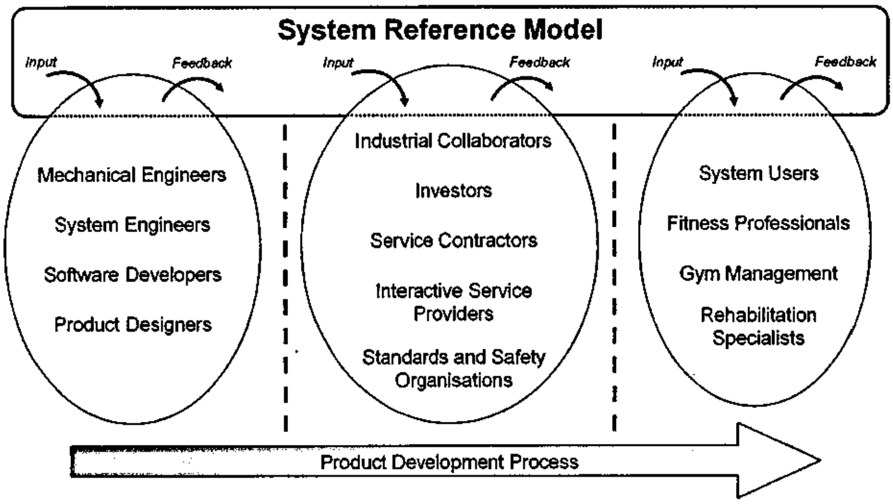


Figure 3.2: Potential system model interactions during the product development process.

3.2 Selection of a candidate modelling framework

Selection of a modelling concept for the purpose of representing the operation of a computer integrated exercise system requires a set of criteria against which their suitability can be accessed. Following a critical review of current modelling techniques, an enterprise modelling approach was identified as the most suitable solution for modelling an exercise system.

Although the precise features of an enterprise modelling technique will vary according to the particular application, the fundamental principles fulfil the major modelling requirements. Enterprise modelling covers a range of operational aspects including the basic information view adopted by generic modelling tools. In order to produce a complete representation of the proposed exercise system, additional enterprise modelling perspectives can be employed. The operational actions performed by the system are formalised using activity models while the available resources and their configuration presented in the resource model. Organization models can be used to formalise the structure of the exercise system and decision making models could be constructed to provide additional behavioural details.

Enterprise modelling techniques may not be suitable for representing all aspects of a computer integrated exercise system but this approach ensures that a standardised set of models is produced which communicate system knowledge in a clear, well structured manner and supports decision making during the development process. The flexibility of enterprise models allows changes to be made efficiently and thus alternative solutions can be evaluated to produce a robust system.

3.2.1 Current approach to exercise system modelling

A review of state of the art exercise system research and development literature (see Chapter 2) revealed that a consistent approach has been taken for the documentation and visualisation of system related information. A basic flow chart technique was found to be the preferred modelling method regardless of specific operational variation (Hickman, 2004; Watterson *et al.*, 2007). Flow charts can be defined as formalised diagrams which use graphical symbols to illustrate a logical sequence of activities, the inputs to these activities and the possible outputs. Using this method, exercise system processes have been decomposed into a series of sequential actions as depicted in the example in Figure 3.3.

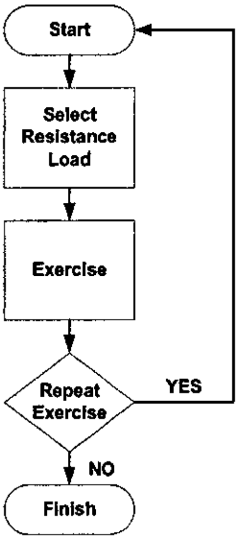


Figure 3.3: Flow chart representation of a simple exercise process.

Using this technique ensures that the diagrams are easy to understand as the constructs are widely recognisable and the process route is clearly mapped (Aguilar-Saven, 2004). Flow chart modelling is an easy method to learn and allows information to be captured quickly and relatively efficiently as the exact modelling methodology is not rigidly defined. However, the generality of the constructs used in flow chart models and the lack of a formal approach to model generation is a major weakness of this method (Aguilar-Saven, 2004). Differentiation between processes / activities and their respective operational levels is not possible and the inability to define task distribution makes it difficult to give a relative overview. Thus, it is clear that in order to improve the modelling of exercise system information, a more structured framework which utilises modelling constructs in a formalised manner is required.

3.3 Analysis of suitable modelling frameworks

There is a vast number of enterprise modelling techniques with differing viewpoints and procedures that could be utilised to represent a computer integrated exercise system. A single approach will not be suitable for every application and therefore it is important to asses the suitability of each method based upon its particular methodologies and modelling constructs. A brief review of the major enterprise modelling techniques which are commonly referred to in both research and industrial literature has been given below.

3.3.1 IDEF

The Integration Definition for function modelling (IDEF) suite of modelling techniques was developed in the early 1980's as a means of providing a standard modelling and analysis method for business process engineering (ICAM, 1981). Initially based on a structured modelling methodology known as the Structured Analysis Design Technique (SADT) in which the system is decomposed into functional elements, IDEF has been expanded to form a set of discrete tools. For the purpose of system modelling, there are two IDEF tools that are directly applicable, IDEF0 and IDEF3.

IDEF0 is based on SADT concepts which were used to define enterprise functionality. This is achieved by using a strict methodology and hierarchical structure for modelling decisions, actions and activities (DeWitte & Porteau, 1997). The basic IDEF0 modelling constructs are simple block diagrams supported by text and arrows that define the relationships and connections between functions. These simple representations indicate the input, control, output and support mechanisms associated with each activity. IDEF0 is a popular tool for systems modelling as it is simple, easy to understand and is supported by a number of commercially available software packages. However, IDEF0 does not support dynamic modelling of the system which limits the scope for process optimisation and the modelling constructs and methodology lead to semantically imprecise models.

IDEF3 differs from the approach taken in IDEF0 by defining business process behaviour (Mayer *et al.*, 1992). The IDEF3 Process Description Capture method is based on two modelling concepts; process flow description and object state transition description. The process flow description represents how the system operates through the relationships which are formed. The object state transition description identifies the objects involved in a process and the state changes that occur during the associated activities.

Although the IDEF3 tool has been used in several areas of business process engineering (DeWitte & Pouteau,1997) this technique does not capture all of the knowledge that is required for complete enterprise modelling. As with IDEF0, IDEF3 essentially creates a static model that represents the state of the system at any given point in time and does not allow dynamic behaviour to be investigated. The rigid methodology enforced in IDEF0 is not emulated in IDEF3 which allows the modeller additional freedom when creating the model and can thus can lead to important behavioural omissions. The differing focus descriptions which are key to the IDEF3 approach allow a more complete model to be created although the interaction between these diagrams is ill defined and an appropriate methodology is not specified in the description.

3.3.2 CIMOSA

The computer integrated manufacturing open systems architecture (CIMOSA) was developed by the AMICE European consortium (ESPRIT Consortium AMICE, 1993) and supports the process oriented modelling of manufacturing enterprises. The CIMOSA reference architecture provides a method for modelling all stages of the manufacturing enterprise life cycle from requirements definition through to implementation. CIMOSA utilises a common set of modelling constructs which cover different levels of generality and defines a specific framework that allows the modeller to approach the modelling task from differing view points. These perspectives include but are not limited to; function, information, resource and organisation (Kosanke, 1995).

A core aspect of the modelling framework defined in the CIMOSA architecture is the formal decomposition of the enterprise model into logical elements. The axis along which a particular approach can be selected and utilised to produce a system model is shown in Figure 3.4. This focus specific model can be assembled with similar sub-models to build a complete representation. The enterprise modelling framework proposed in the CIMOSA approach is based upon the two architectures, a reference architecture and a particular architecture (Vernadat, 1996). The particular architecture encapsulates those models which represent actual business processes. The reference architecture is sub-divided further based upon the generality of the model into generic and partial levels. The generic level defines the basic enterprise modelling constructs whilst the partial level is composed of collections of semi completed models which are grouped together to represent common business processes. These templates are stored and can be inserted directly into the particular architecture to save time during the modelling process.

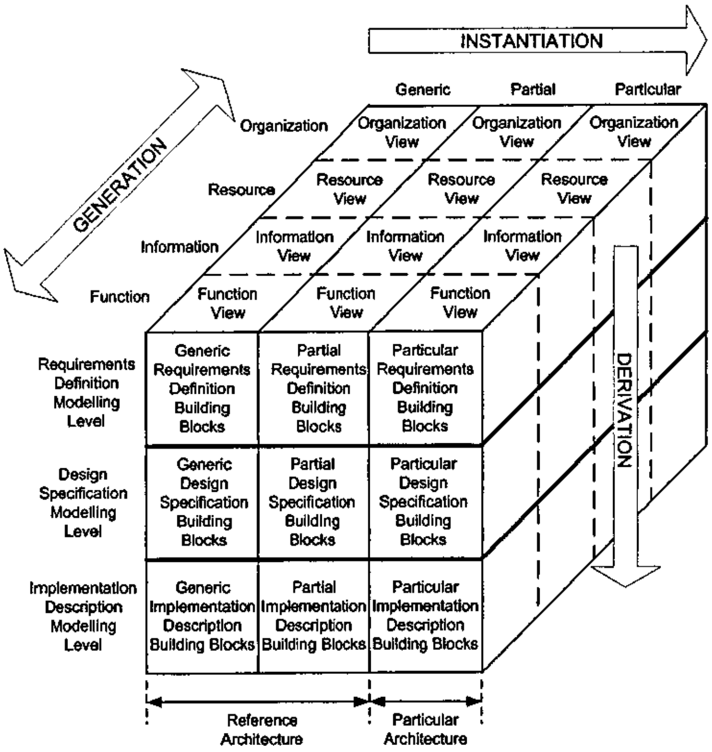


Figure 3.4: CIMOSA cube: System decomposition and model focus definition.

In order to maintain the integrity of the parent enterprise model the CIMOSA architecture is built upon a set of basic building blocks (Kosanke, 1995). CIMOSA modelling constructs utilise object oriented principles (see section 3.3.5) including that of inheritance. Inheritance describes the hierarchical structuring of common objects with similar characteristics into groups or object classes. These classes have been categorised to describe behavioural rules, functional operation, information and resources requirements and organisational aspects of the enterprise as shown in Figure 3.5.

The CIMOSA modelling framework is an effective approach to business process modelling but has been criticised for producing large and complex models and lacks a formal specification for graphical notation (Aguilar-Saven, 2004). Also CIMOSA models capture static representations of the enterprise and have not been employed to model dynamic systems.

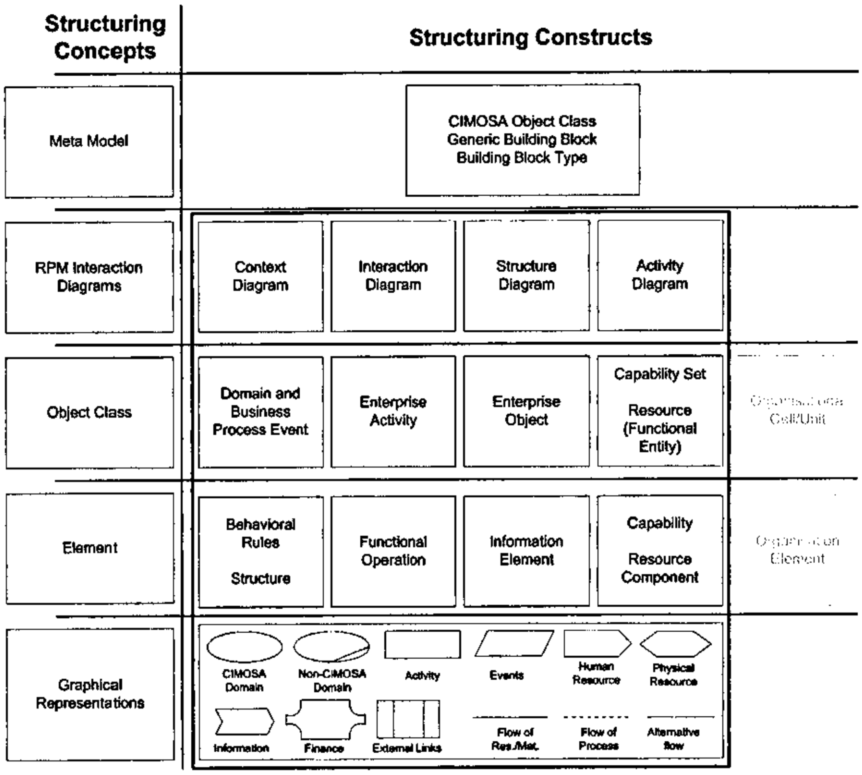


Figure 3.5: CIMOSA modelling constructs.

3.3.3 GRAI

The Graphs with Results and Activities Interrelated (GRAI) integrated methodology was developed at the University of Bordeaux in France as a means to model automated production systems (Doumeingts, 1989). Initially this technique focused on modelling decisional structures in manufacturing systems. The GRAI integrated methodology (GIM) is an extension of the original GRAI concepts which broadened the scope of the initial approach to create an integrated enterprise modelling methodology (Chen & Doumeingts, 1996).

The GRAI methodology utilises four basic views which can be utilised to categorise the system into physical, functional, decision and information elements (Doumeingts, 1989). This framework allows the modeller to represent complex system and / or business processes using partial models produced from different perspectives. GIM provides a number of modelling formalisms used to represent the process in each of the views. For example, IDEF0 is used for describing the functional / physical view. GRAI grids and GRAI nets, unique tools to the GIM methodology, are used to describe the decisional aspects of the system (Chen *et al.*, 1997). To support the modelling process, GIM also specifies a modelling framework and a structured modelling approach in order to aid in the creation of accurate and appropriate enterprise models.

GIM provides a well structured approach to enterprise modelling and the GRAI grid has become a useful analysis tool. However, the approach is criticised for duplicating information in different models (Vernadat, 1996), providing only a static representation of the enterprise and does not provide a formal method for supporting system implementation and behavioural design (Li, 1997).

3.3.4 Object oriented methods

This approach is primarily based around a single modelling construct known as an "object" which is transformed by activities in the system process. An object is defined by the states that it may achieve during the process and the behaviour it exhibits to internal and external inputs. An object will change state when a behavioural function is activated by a message from a sender object. A complete model is composed of a series of objects which communicate by sending and receiving messages and reacting accordingly. Using this method, both system function and information can be expressed explicitly.

The single modelling construct approach utilised in objected oriented methods is a particularly desirable feature. By basing the system on a basic building block, it is possible to identify common properties that appear repeatedly in a number of objects. These properties can be grouped and used to create further objects without having to specify each individual characteristic. A group of objects which exhibit similar properties can be organised into classes and stored for use in subsequent system models. The creation of an object class library can improve the consistency of a model and increases the efficiency of system implementation (Coed & Yourdon, 1991).

There are a number of techniques that have been developed for object oriented modelling although UML (Unified Modelling Language) is widely considered as the industry standard. UML provides the modeller with a structured methodology for generating models using the object oriented modelling concepts. This technique defines a set of different diagrams which can be used to describe both static and dynamic enterprise aspects. A process of system refinement is possible using UML through the creation of executable models (Marshall, 1999).

Although object orientated methods have proved to be effective in modelling computer software there are problems when the approach is used for representing other systems. It can be difficult to transfer enterprise features such as processes and resources into discrete objects and although there has been considerable research in the field, there are still few well-defined object classes for effective re-use in modelling enterprises (Vernadat, 1996).

3.3.5 Petri-nets

Petri-nets were initially developed as a graphical and mathematical tool for modelling the behaviour of computer systems (Peterson, 1981). These systems exhibited concurrent or parallel operational characteristics which could be represented and analysed effectively using this technique. There are two basic modelling constructs of the Petri-net approach; places and transitions. Places symbolize the states of the system while the transitions are the actions that can be taken during the process. These constructs are linked by "arcs" that represent the flow of "tokens" from one place to another. The behaviour of the system is represented by the movement of tokens between places which are initiated by the activation of a transition (Peterson, 1981).

The techniques utilised in this modelling framework allow the system to be modelled in a form that allows resource and scheduling conflicts to be identified and ensures that any planned process synchronisation is correctly aligned. The models produced using the Petri-net approach provide an unambiguous representation of the structure of the system. Quantitative analysis may be to be undertaken using this approach through simulation or other formal analysis method.

The basic Petri-net approach to enterprise modelling has been criticised for its lack of hierarchical structure. The lack of a defined decomposition process and an interface definition procedure for dividing complex systems into meaningful elements limits the size of the system that can be modelled. This issue is compounded due to the omission of any data modelling concepts. The size of the models become excessively large as data manipulation was modelling using the basic modelling constructs and Petri-net structure (Aguilar-Saven, 2004).

Further development of the Petri-net framework to resolve the initial modelling limitations lead to the creation of a number of expansion methods. For modelling a system such as that under investigation in this paper, the most relevant development of the Petri-net framework developments is known as Coloured Petri-nets (Jenson, 1997). This technique utilises a colouring system to define the data types within the diagram and introduces hierarchical structuring schemes for producing simplified models of complex and large enterprise systems.

3.4 Evaluation of candidate system modelling frameworks

Despite continual research activity, the creation of a generic modelling framework for capturing information at all stages of the system / enterprise life cycle and from all views points has not been achieved. Thus, in order to select the most appropriate technique it is essential to understand the purpose of the model to be constructed and the particular strengths and weaknesses of the approaches available. Various studies have been conducted to classify enterprise modelling techniques to ensure that a reasoned choice can be made when selecting a particular framework.

A simple selection framework proposed by Augilar-Saven (Aguilar-Saven, 2004), introduced a two axis classification procedure. This scheme orders each approach according to its change capabilities and groups the model using its perceived purpose. The change capabilities of the model refer to the level of interaction that exists. The ability to make changes to a particular model without having to remodelling the entire system is referred to as an active approach, while modelling techniques which require the information to be reconstructed are referred to as passive. The framework defines four discrete model proposes (i) descriptive models for learning about a system, (ii) descriptive analytical models for decision support of process development and design, (iii) enactable or analytical models for decision support during implementation, and (iv) monitoring and enactable models for information technology support.

The enterprise modelling frameworks discussed in section 3.2 have been classified using this selection framework in Figure 3.6. If an effective tool is to be chosen then the purpose of the model must be specified and the required level of change determined. During the development of a computer integrated exercise system described in this thesis, the main function of the model is to formalise the processes and structure of the system thereby capturing and presenting specific knowledge related to exercise procedures. Decisions will need to be made regarding the design of these processes and therefore some analysis may need to be undertaken. Software development is likely to form a major component of the development process, thus IT enactment support will be a useful attribute. Research trends in advanced training techniques indicate that additional processes may need to be integrated into the system late in the development phase or post implementation. To support the system efficiently throughout its specification, design, test, manufacture and recycle lifecycle, a modelling approach that exhibits active change capabilities is essential.

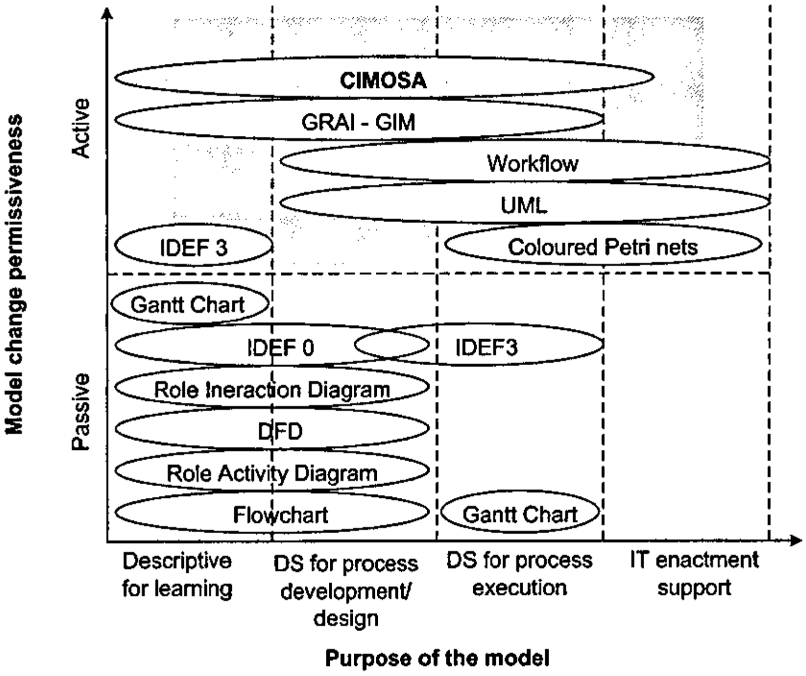


Figure 3.6: Enterprise model selection framework. Adapted from Augilar-Saven (2004).

The shaded areas in Figure 3.6 represent the required modelling focus for a computer integrated exercise system. From the diagram it is clear that the CIMOSA architectural framework is the only enterprise modelling technique which fulfils this partial specification for an exercise system model in a single integrated method. It has been acknowledged that a number of different tools could be utilised, which individually may provide a greater depth of focus from certain aspects. However these tools can not be directly related to one another and thus compromise the integrity of the model. The selection framework developed by Augilar-Saven presents a guide for further development of enterprise modelling analysis tools using the two basic criteria identified. Increased suitability is likely to be achieved if the modelling technique is also assessed against additional criteria such as those discussed by Fox and Vernadat (Fox, 1994; Vernadat, 1996).

The additional characteristics defined in these studies include; generality, scope, granularity, precision, competence, efficiency, perspicuity, transformability, extensibility, consistency, completeness and scalability. The axis used by Augilar-Saven for the two dimensional grid can be related to the competence and extensibility characteristics. If the remaining attributes are used to assess the enterprise modelling frameworks detailed in section 3.2 then there are two main approaches which satisfy the requirements for effective modelling of a computer integrated exercise system. The IDEF suite of tools and the CIMOSA architectural framework both provide good scope, granularity and transformation. The CIMOSA approach could be considered to be a more complete and consistent solution as the framework is composed of a set of integrated models rather then the discrete modules utilised in IDEF. The precision of the model, or the ability of the model to represent reality, is dependent upon the particular modelling constructs used by the modeller in the CIMOSA architecture. IDEF provides a set of defined modelling formalisms which may aid understanding, or perspicuity, as the constructs are not open to interpretation. Both of these methods should result in the creation of efficient models and can be transformed relatively easily for additional process simulation and enactment. Scalability of the proposed modelling techniques is favourable although the data requirements for models of high complexity can be large.

From this appraisal, the CIMOSA architecture has been selected as the approach most suitable for modelling a computer integrated exercise system. CIMOSA concepts allow all of the necessary model views to be created in a structured manner using a well-defined methodology. The impact of the limitations upon the effectiveness of the modelling process was acknowledged. It was decided that the planned system model would not be compromised by the short comings of this approach. A formalised abstraction method developed through research conducted at Loughborough University will be used to define the modelling constructs used within the CIMOSA framework to form a complete solution (Monfared, 2000). The magnitude of system complexity is relatively low and therefore data requirements will not be excessive.

3.5 CIMOSA modelling formalisms

The CIMOSA architectural framework has been utilised by European and International organisations as a basis for determining and formalising a standard approach to enterprise modelling. This approach whilst providing a detailed decomposition of the business at a high level does not specify the basic modelling constructs which represent the fundamental process elements. The main elements of the CIMOSA approach have been identified in Figure 3.7 (Zelm, 1997).

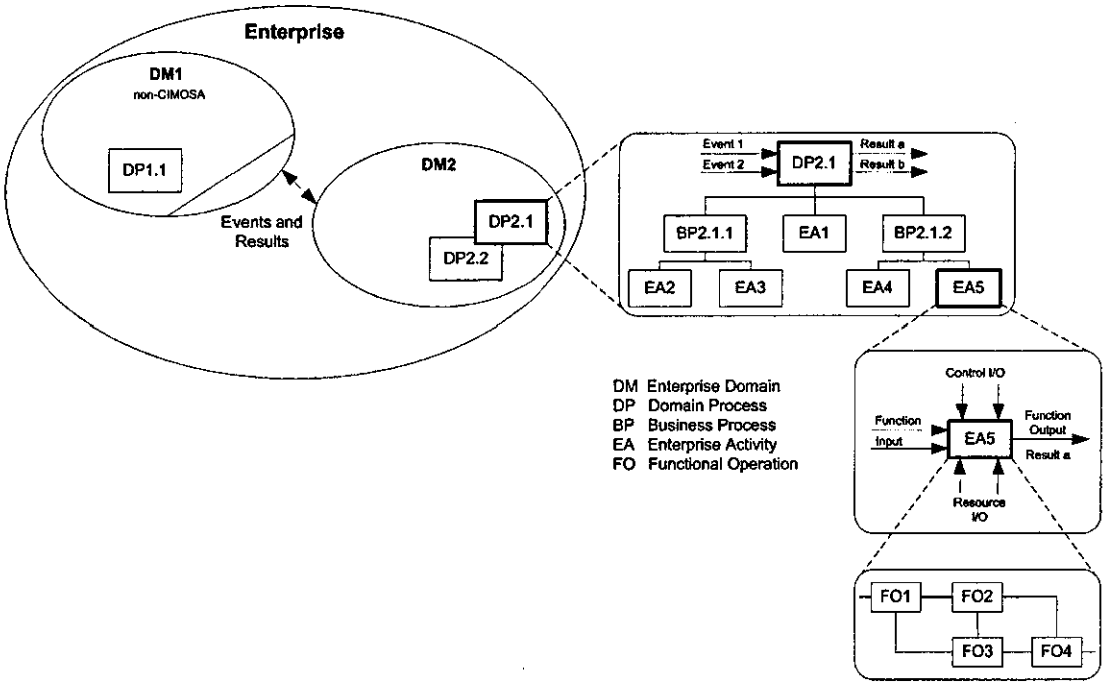


Figure 3.7: CIMOSA modelling elements.

The system / enterprise under investigation is divided into a series of domains (DM). These domains are described as functional areas that are aligned to achieve some goal (Vernadat, 1996) or complete a task within the operation. It is only necessary to analyse domains which are of direct interest to the study although all relationships must be defined. Domains are composed of a set of core processes known as domain processes (DP), and communicate via events raised and results produced. An event triggers a set of business processes (BP) and enterprise activities (EA) in the domain process which lead to the production of an end result. Enterprise activities transform objects using resource and control inputs and a linked by a set of behavioural rules. The outputs from each enterprise activity are also defined. Enterprise activities are further decomposed into functional operations (FO) which represent the elementary processing steps. At this level a series of functional entities are identified which have specific capabilities to allow particular operations to be completed.

Research conducted at the MSI Research Institute (Loughborough University) has lead to the development of a hierarchical diagram structure, Figure 3.8, which utilises a formal set of modelling constructs for modelling a wide range of different systems (Monfared, 2002; Monfared, 2007). The diagrams outlined in this approach represent alternative, but complimentary views of the system and demonstrate how CIMOSA concepts can be implemented graphically. Four types of diagram: the context diagram, an interaction diagram, a structure diagram and an activity diagram have been specified which illustrate the details and interaction between domain processes, businesses processes and enterprise activities (Aguiar, 1995). The constructs defined in this approach illustrate CIMOSA and non-CIMOSA domains, activities, events, information, human resources, physical resources, finance and external links. Object inputs / outputs are represented by the flow of materials and resources, process flows and alternative flows. These modelling formalisms allow all aspects of the system to be modelled but are primarily based on the CIMOSA function view.

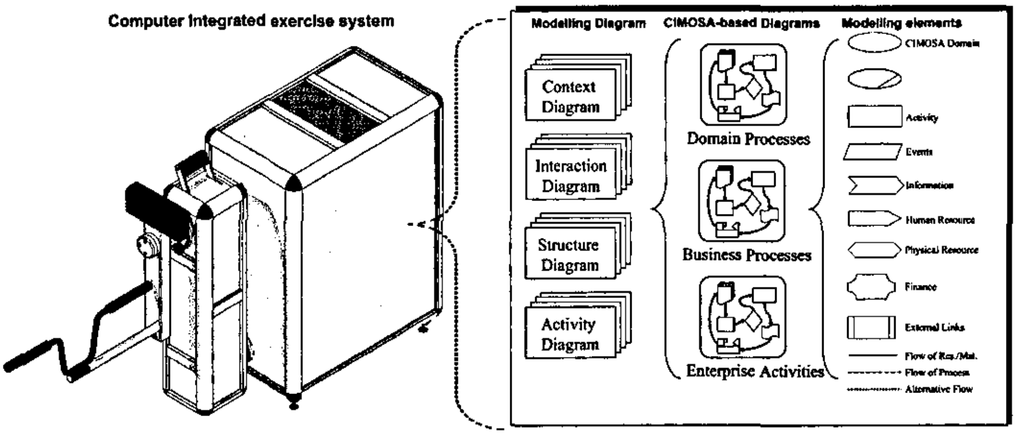


Figure 3.8: CIMOSA modelling constructs for the modular exercise system.

3.6 Discussion of the resultant exercise system models

Using the proposed process modelling approach and the CIMOSA architectural framework, a set of diagrams have been developed which illustrate the operation of a computer integrated exercise system (see Appendix B). The diagrams featured in the following sections do not represent the system architecture in its entirety but present the methodology and formalisms used during the modelling process and how these relate to real world processes. At present there are no software tools to support the development and enactment of CIMOSA enterprise models and therefore the diagrams presented in this research are essentially paper-based representations of the system.

3.6.1 Computer integrated exercise system context diagram

The context diagram is used to define the domains to be modelled using CIMOSA formalisms. The overall context diagram for the computer integrated exercise system is illustrated in Figure 3.9. The system is built around the fundamental processes involved in preparing, participating and completing any type of exercise routine. Integration of computer control, monitoring and visualisation increases the domain complexity which has been decomposed into seven key domains. These include Setting Up, Exercise Configuration, Monitoring Exercise, Exercise Session, Interactive Help, Safety and Emergencies and Administration. Each of the domains identified have been investigated and therefore there are no non-CIMOSA domains present. The domains shown in Figure 3.9 represent the principle operational modules which have differing functionality but interact to create the overall system dynamics.

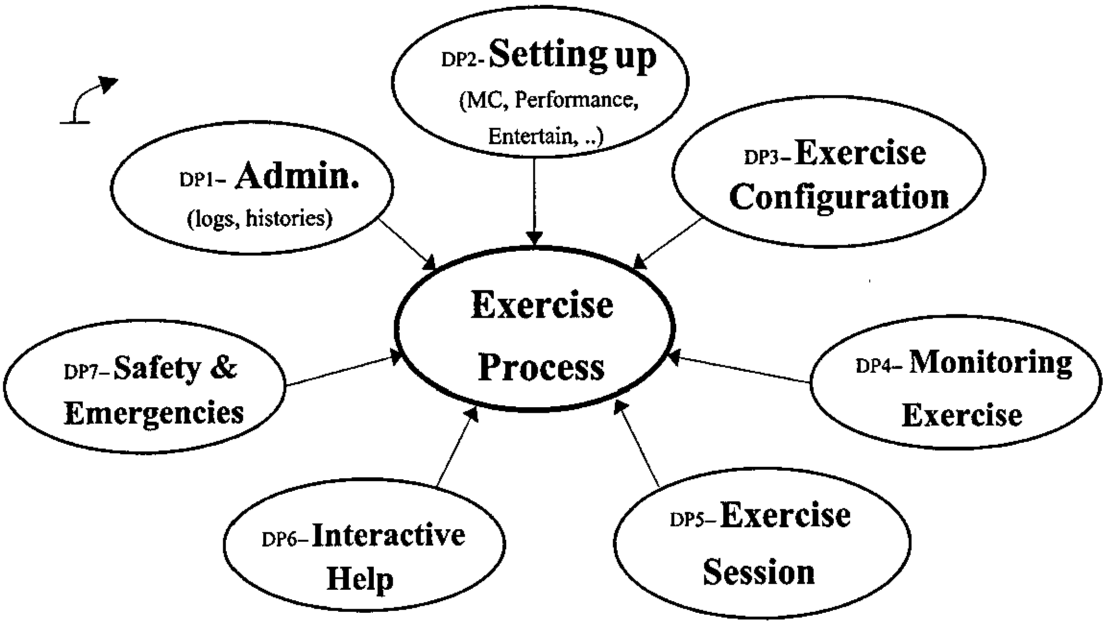


Figure 3.9: Modular exercise system CIMOSA context diagram.

3.6.2 Computer integrated exercise system interaction diagram

Interaction diagrams are used to illustrate the high level exchange of human and physical resources, information and events between domains. The main focus of these diagrams is on the items exchanged rather then the processes themselves. Interaction diagrams are drawn to identify, define, organise and represent the interactions involved between the domain processes (Chatha, 2004). The interactions between three example domain processes in the proposed computer integrated exercise system are illustrated Figure 3.10.

Detailed user information is passed to the Administration domain process (DP1) from physical storage device or via user input. Information concerning the user's age, gender, weight, height, contact details, training experience, injury history and any medical conditions are requested by the Administration domain process (DP1). Domain process Setting Up (DP2) may either call for the range of motion or one repetition maximum data from the Administration domain process (DP1) or determine a set of new values through user calibration activities. The physical attributes of the actuator selected will restrict the range of exercises and muscle groups that can chosen.

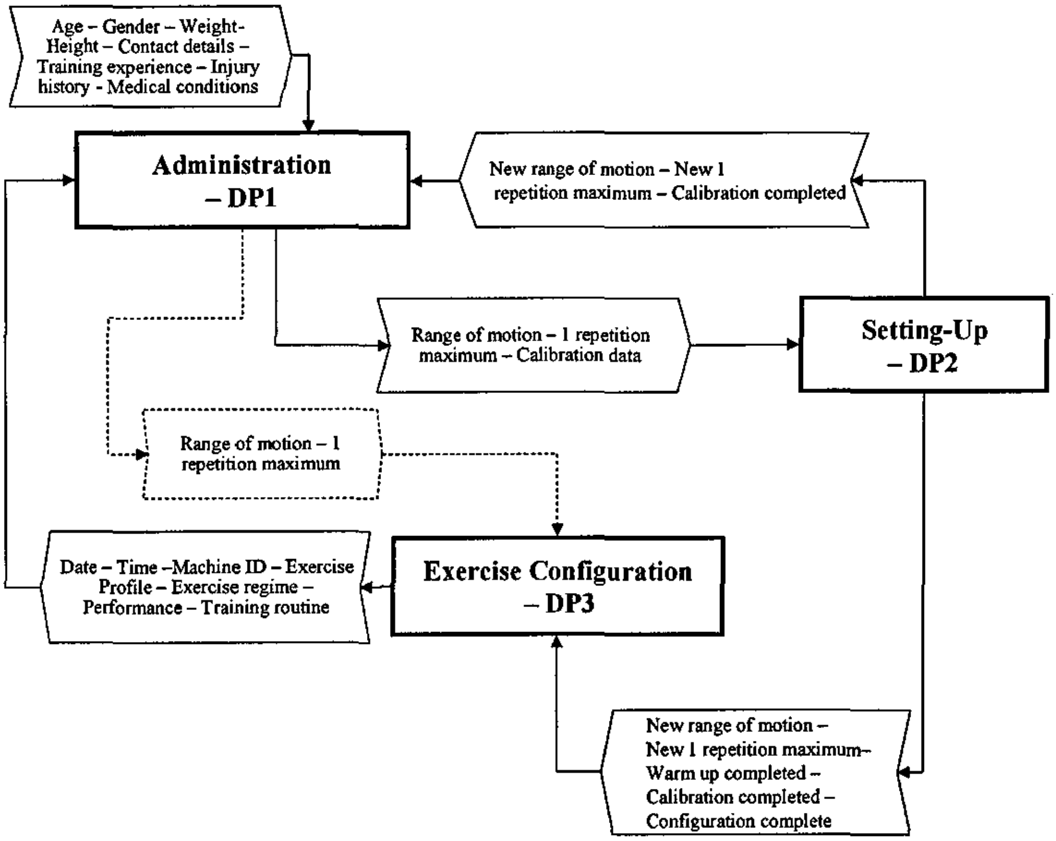


Figure 3.10: CIMOSA interaction diagram for three domain processes.

Exercise Configuration (DP3) receives details of new values for the range of motion and one repetition maximum from the Setting Up domain process (DP2) or may utilise the existing values from the Administration domain process (DP1). Checks to ensure that a warm-up procedure has been completed and the necessary calibration data have been collected will also be transferred. If new values for the range of motion and one repetition maximum have been established then this information will be sent back to the Administration domain process (DP1) together with details of any warm-up or calibration procedures completed.

Information concerning the particular equipment and training arrangements from the Exercise Configuration domain process (DP3) are transferred to the Administration domain process (DP1). These include specifics such as date, time, machine ID, exercise profile, periodisation progress, exercise regime and training routine. The data can be uploaded onto a physical storage device or discarded as the user wishes.

3.6.3 Computer integrated exercise system structure diagram

A full structure diagram for the exercise process domain can be found in Appendix B. Nevertheless a partial illustration showing the Administration and Setting up domain processes is given in Figure 3.11. Structure diagrams provide a graphical method for identifying and structuring enterprise activities and business processes within a domain process. For example the Administration domain process (DP1) is composed of three basic business processes (e.g. User identification (BP11) , New Users (BP12) and Exercise Termination(BP13)) which are further divided into a series of enterprise activates.

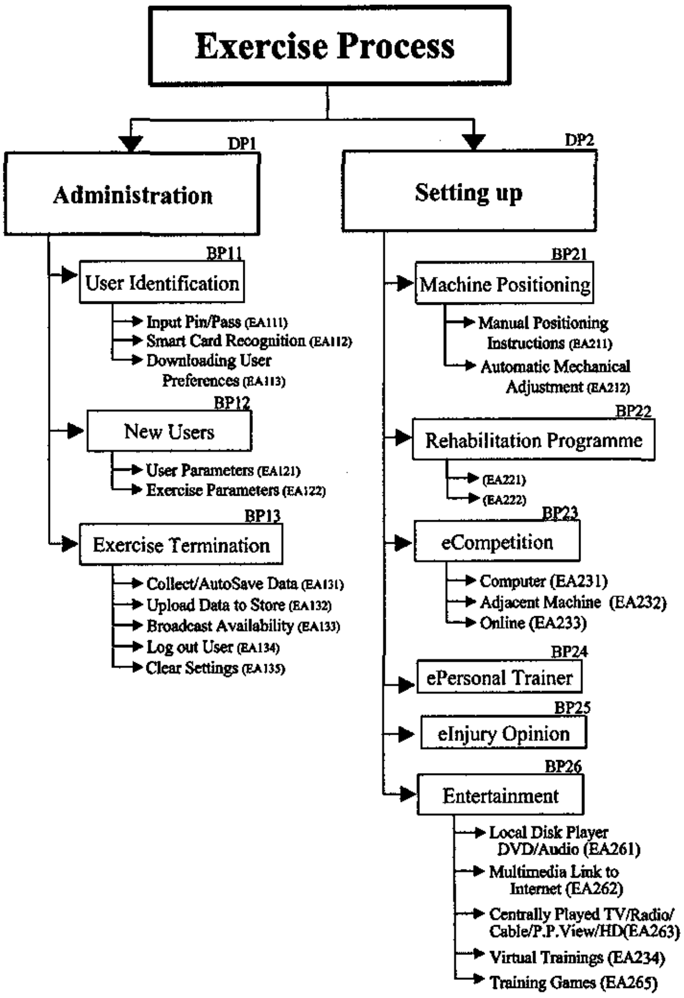


Figure 3.11: Partial CIMOSA structure diagram of the Administration and Setting up domain processes.

These enterprise activities represent the basic functions of the domain process. For example the Exercise Termination business process (BP13) has been divided into five enterprise activities: Collect / AutoSave Data (EA131), Upload Data to Store (EA132), Broadcast Availability (EA133), Log out user (EA134) and Clear Settings (EA135). These enterprise activities define the user options and automated system responses that occur once the current exercise session has been terminated.

3.6.4 Computer integrated exercise system activity diagram

The structure and interaction diagrams discussed above illustrate the hierarchical organisation of processes and activities in the exercise process domain and identify the communication and resource lines which link these elements. However, the information presented is not time-based and therefore the flow of the operations must be defined in a specific sequencing diagram. This type of sequencing data is represented in the activity diagram. The time dependences of the Administration domain process (DP1) are shown in Figure 3.12. Upon initiation the system will prompt the user for identification. Users who are new to the system will be asked to enter some basic data before progressing (EA121) whilst those who have registered previously can download information from a portable storage device (EA112) or access a central database system by password (EA111). Once the system has been activated, registered users can access performance and injury archives or recover previous exercise settings. New users can define their previous training experience and injury status (EA122) for subsequent storage. Once this basic information has been entered the user will be asked to complete the system set up routine (DP2).

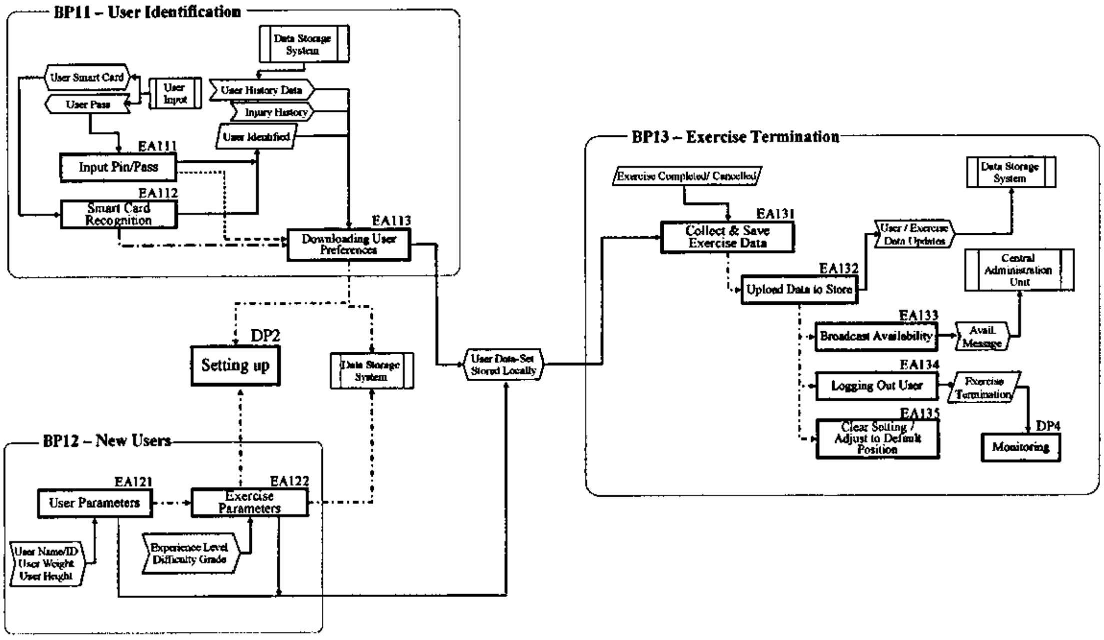


Figure 3.12: CIMOSA activity diagram of the system Administration domain process.

Any data recorded during the exercise process will be stored locally on the host machine. Once the user has finished training, the system will save or discard the information for that session (EA131). If the user decides to save their performance then the data can be uploaded to their portable storage device or transferred to a central networked database (EA132). If data has been stored in the database, the central administration unit will be updated to allow authorised personnel trainers, health care professionals or automated systems to access and assess the information (EA133). The user can then log out from the system and remove their storage key (EA134). The user is free to observe and analyse their performance once the exercise has been terminated by uploading the information from their storage device or by accessing the database from a suitable terminal (DP4). Once a log out command has been received, the system will run through a reset procedure which will return the operational settings to predetermined defaults (EA135).

3.7 Practical applications of a computer integrated exercise system model

Only a sample of the context, interaction, structure and activity diagrams that have been used to represent a computer integrated exercise system have been illustrated in Figures 3.9-3.12. These examples are intended to demonstrate how the basic constructs and methodologies of the CIMOSA architectural framework when combined with the Loughborough University process modelling techniques can be utilised for this novel application. Figure 3.13 shows how this approach has been used to support the development of a computer integrated exercise system human machine interface (HMI) software application (see Chapter 6). The screen shots in the diagram, represent the information and resource interfaces developed for the business processes and enterprise activities identified in the Administration domain process (DP1).

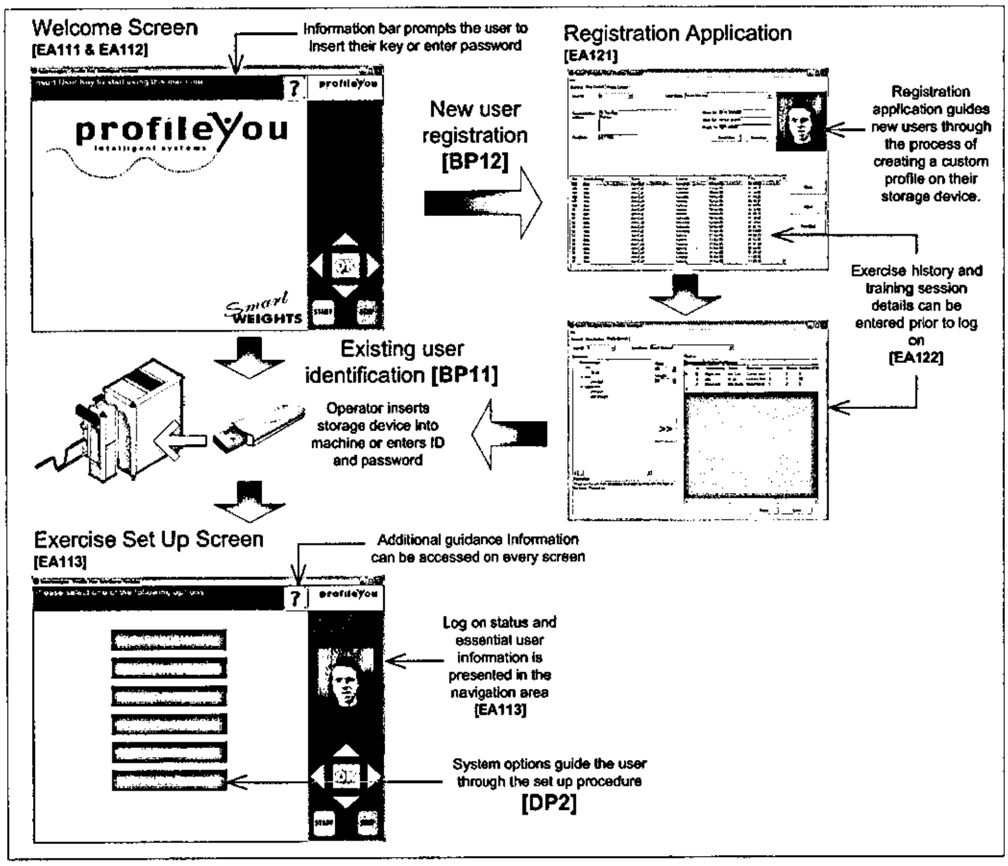


Figure 3.13: HMI sequence to illustrate the underlying structure developed using the CIMOSA diagrams.

An initial welcome screen prompts the user to insert their storage device or enter a password in order to access the central database (EA111 and EA112). Once the system has uploaded the necessary data, key information is presented in the navigation area of the screen to notify the user that the system has accepted the stored details (EA113). A user profile manager has been developed to guide users who are new to the system through the registration procedure (EA121). The application asks the user to enter personal details which are used to construct their unique identification number and provide essential background knowledge. Once the basic data has been entered the user can access more advanced features which allow them to record their previous training experience and define their particular exercise focus (EA122). Once business process BP11 or BP12 have been completed, the software automatically directs the user through the system set up procedures (DP2).

3.8 Summary

The purpose of this research was to evaluate and select a suitable technique for identifying, capturing and presenting information relating to computer integrated exercise systems. Existing systems modelling techniques were found to be complex unstructured and semantically imprecise. In order to develop a more effective system it was proposed that a more meaningful and efficient modelling technique should be adopted. A review of general systems modelling approaches resulted in the detailed analysis of enterprise modelling techniques. This particular approach was selected for its process oriented concepts which could be used to effectively represent the operational requirements of a computer integrated exercise system.

The CIMOSA architectural framework was selected as the candidate enterprise modelling technique and the process modelling diagrams developed at Loughborough University used to provide the graphical notation for system representation. The context, interaction, structure and activity diagrams illustrated in this paper have demonstrated how the proposed constructs and methodology can be used to model a computer integrated exercise system in an effective manner. A complete system model has been created by the MSI research institute at Loughborough University during the development of a novel training system. The various models produced have helped to clarify understanding of the complex operational procedures, identify physical and information resource requirements and assisted in the development of the system behaviour. The CIMOSA architectural framework has provided a formal structure for the model and the object oriented constructs have resulted in the identification and re-use of common components in different domain processes. The practical development of both hardware and software systems have been based on the detailed system models created at the initial stages of the project.

Although the application of a system / enterprise modelling technique has been shown to be an effective method for modelling a computer integrated exercise system, research and development of new techniques such as CIMOSA is a continual process. Alternative approaches which could resolve the shortcomings associated with the preferred method (e.g. model complexity and time requirements) are likely to supersede this approach in the future. Therefore, it is important to continue to monitor advances that are made in enterprise modelling but also improvements in general system modelling techniques. Reviews such as that presented in this chapter are important in ensuring that the development of new and increasingly complex systems is completed efficiently. This can be achieved through the adoption and implementation of modelling tools which support the effective capture, presentation and simulation of system based knowledge.

Chapter 4

Concept development and embodiment design

4.0 Introduction

The requirements detailed in Chapter 3 precisely define the quantitative and qualitative features of the proposed resistance exercise system. In order to provide an effective solution that is capable of satisfying all of the requirements, the system has been decomposed into an ordered set of sub-systems. The conceptual systems that have been identified / developed and the analysis techniques used to select the final designs are briefly discussed in this chapter. Once suitable sub-systems are established, a process of embodiment design is followed to produce a detailed, integrated mechanical and electro-mechanical assembly.

4.1 System design methodology

Formalised methods for product development are widely documented in product design and manufacture literature (Ulrich & Eppinger, 1995). These procedures generally follow an iterative cycle of design, analysis and refinement. For the purpose of developing the modular exercise system, a modified approach has been adopted which utilises the basic principles of these established methods. Upon examination of the operational requirements of the exercise system, a number of discrete mechanical elements were identified that provided fundamental operations which, when combined, produce the overall desired functionality.

The complete system was decomposed into a set of basic mechanical sub-systems as shown in Figure 4.1. The design of customised parts and specification of existing components for each sub system was completed independently, in a sequential manner, using the standard development process. Although each sub-system was primarily developed in isolation, consideration was given to interaction with the other elements at the analysis and refinement stages. This decomposition process added focus to the development of each mechanical element to ensure the most effective solution was achieved without restricting the originality of the concepts created at the early stages of the design process.

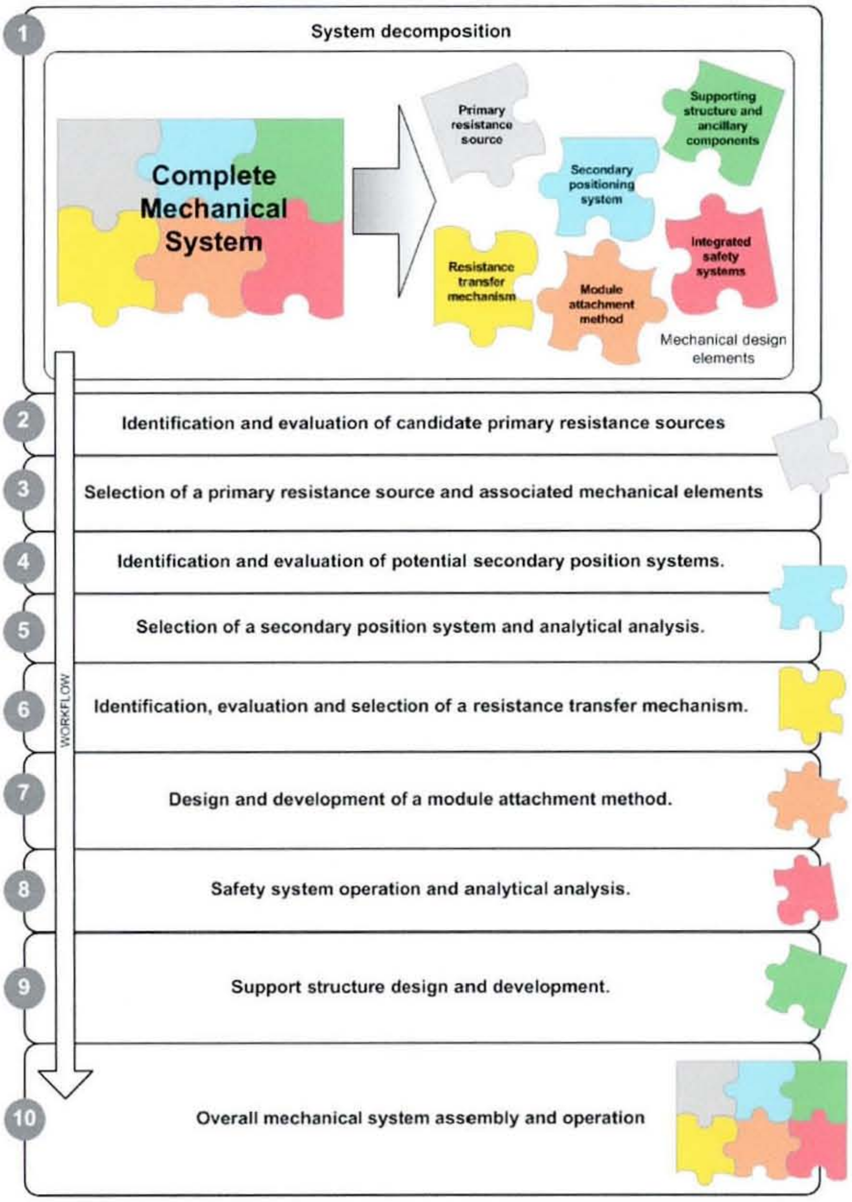


Figure 4.1: Diagrammatic representation of the exercise system design process.

Development of a primary resistance source for providing an output against which the user will exercise was identified as the principal sub-system for development as shown in Figure 4.1. Having identified a suitable resistance system and associated transmission components, a method for altering the relative location of the resistance output was established to ensure that programmable resistance could be applied through the axis of each users joints for each exercise configuration. In order to transfer the output of the primary resistance source to the various secondary locations, an additional sub-system was required to transmit the power between each point. Since the ability to provide multiple output locations allows the system to be configured for different aerobic and anaerobic exercises, a system for connecting the resistance output to each training attachment was also required.

Any modern system which features some form of interaction with a human user will generally include a series of interlocked safety systems in order to comply to legal requirements. Having defined the previous sub-systems in the development process and identified any latent safety features, additional mechanisms were developed to enhance the level of user protection (Note: mechanical safety features are integrated with electromechanical and software safety mechanisms within the final solution). The final sub-system to be developed was the support structure and enclosure which provides mounting locations and protection for internal sub-systems whilst protecting the user and providing overall system stability. Using this method, the sequential development of each sub-system has resulted in an overall mechanical solution which provides optimum performance for each operational aspect and when integrated together, satisfy all of the requirements discussed in Chapter 2.

4.2 Analysis of potential resistance sources

A research approach based upon matrix evaluation and house of quality procedures (Ulrich & Eppinger, 1995) was initially adopted to identify potential resistance systems using information from both existing products and state of the art technologies. At this stage, solutions which exhibited unsuitable characteristics or fundamental limitations were discarded. Using this method, a set of candidate variable resistance sources that could provide all or a proportion of the functionality defined in product design specification were selected for further analysis as illustrated in Figure 4.2.

The basic characteristics of each resistance system were analysed and the information used to produce a quantitative summary of each solution for evaluation purposes. The results of this analysis were used to assess each solutions suitability and identify the most promising system for further development. The selection criteria listed in Figure 4.2 represent key aspects of the design specification which influence the selection of a primary resistance system. Each criterion was assigned a weighting to represent the relative importance of each feature. A high weighting indicates an important design requirement, whilst a low weighting signifies an attribute that is desirable but not essential. Using expert knowledge and general product information, each solution was graded on its ability to satisfy the particular criteria as indicated in the un-shaded column. A grade of five signifies that the system fully meets the criteria while a score of one indicates that the approach fails to offer the required features. The product of the relative weighting and the chosen grade, shown in the shaded column, were summed and an overall aptitude figure established for each variable resistance source.

A number of conclusions can be drawn from the evaluation matrix. Examining those criteria which had been considered as essential features and thus weighted heavily, it was clear that utilising an electrical resistance would provide the required variable profile capabilities over a suitable load range. The costs of developing an electrical resistance system were relatively high but these were offset by good availability and safety, excellent functionality and minimal size requirements. The overall figures from this initial selection process clearly show that electrical resistance appears to offer the most efficient and effective solution to the provision of a resistance system for the experimental exercise device.

Selection Criterion	Relative Weighting	Resistance Source											
		 Weight stack + Cam		 Friction		 Elasticity		 Magnetic Resistance		 Fluid Resistance		 Electrical Resistance	
Ability to provide instantaneous variable load profile	10	2	20	2	20	1	10	4	40	4	40	5	50
Active loading	10	4	40	1	10	3	30	1	10	1	10	5	50
Bilateral loading	8	5	40	1	8	3	24	1	8	5	40	5	40
Velocity independent resistance	10	3	30	2	20	4	40	2	20	2	20	5	50
Broad torque capabilities	9	5	45	3	37	2	28	4	36	5	45	5	45
Efficient	8	4	32	3	24	3	24	4	32	4	32	4	32
Minimal space requirements	4	2	8	3	12	2	8	4	16	3	12	5	25
Low cost	6	4	24	4	24	4	24	3	18	2	12	2	12
Durable	6	4	24	1	6	2	12	4	24	3	18	4	24
Safe	10	3	30	3	30	4	40	3	30	5	50	4	40
Easy to use	8	4	32	4	32	2	16	4	32	4	32	4	32
Commercial availability	4	5	20	3	12	2	8	3	12	5	20	5	20
Low noise production	5	5	25	2	10	5	25	5	25	2	10	3	15
Low weight	2	1	2	4	8	4	8	3	6	2	4	3	6
Simple control	6	5	30	4	24	5	30	4	24	3	18	4	24
Total		56	**402**	40	**277**	46	**327**	49	**333**	50	**363**	63	**465**

Sum of scores

Sum of (score x weighting)

Proposed primary resistance source

Figure 4.2: Quantitative analysis of potential resistance sources against key selection criteria.

4.2.1 Electrical resistance investigation

Having identified electrical resistance as the preferred resistance source, the alternative drive solutions and component choices were examined and a detailed selection made in reference to the predetermined system requirements. In general, an electrical resistance system such as that investigated is composed of a series of connected elements which transmit torque from the source to the output. A group of components arranged in such a configuration is known as a rotary power transmission system (Pitts, 1988). A system element may be a shaft, a coupling, the drive mechanism or a gearbox which, when combined, form part of the mechanical power transmission train.

The system utilises the basic principles of rotary power transmission, to ensure that the torque supplied by the electrical resistance is translated effectively for use as a resistance training input. For efficient operation, the system must exhibit minimal energy losses through each rotary power transmission element. Careful design is required to reduce frictional resistance, inertia, torsional movement and backlash (Pitts, 1988). In order to minimise control requirements and any post-processing of data, it is essential that both the torque and velocity characteristics of each power transmission element are closely matched.

A rotary power transmission system can be divided into five functional elements: the primary input source, power modifiers, actuators, feedback devices and coupling systems. Each of these rotary power transmission elements is composed of an array of mechanical systems as shown in Figure 4.3. Appropriate element selection is conducted using information regarding the unit output, required inputs and overall system specification. In general, the primary input source should be defined first and the other elements configured to produce the desired rotary power transmission characteristics.

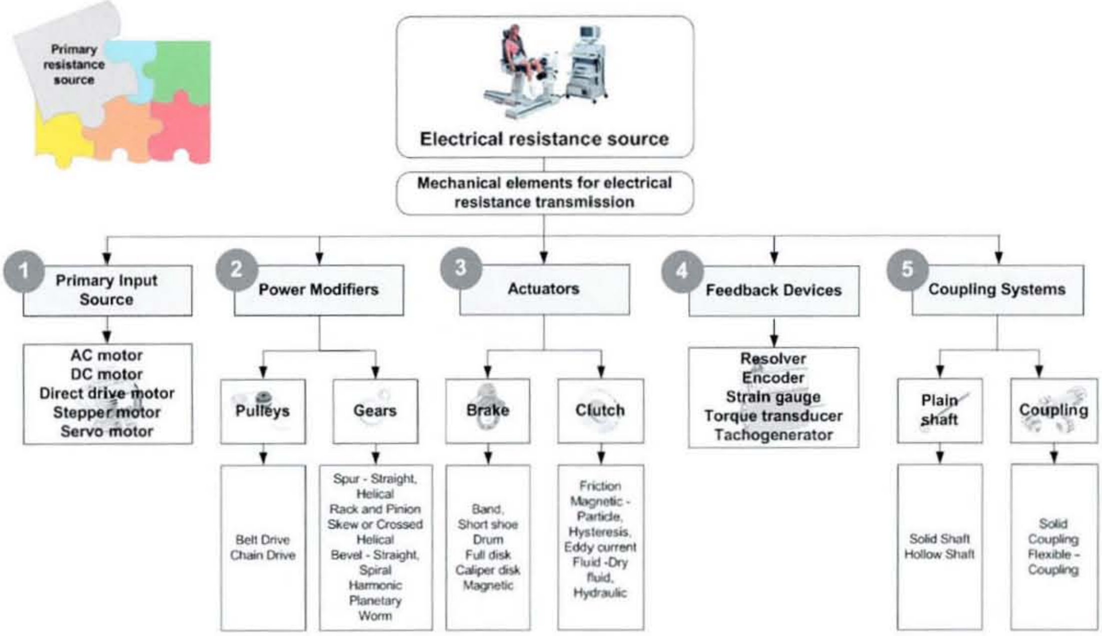


Figure 4.3: Identification of the mechanical elements available for the electrical resistance transmission.

4.2.1.1 Primary input source selections

An iterative selection process was used to establish a short list of alternative solutions from the vast range of commercially available electric motors. In order to ensure the correct unit was chosen, fundamental design attributes including load conditions, power, speed, environmental protection and electrical supply were identified as primary screening parameters. Using the data defined in Chapter 2 and the product design specification, the maximum operational requirements of the primary input system could be summarised as follows requiring a maximum torque of 350Nm and velocity of 500 degrees per second. The system was intended to offer bi-directional movement and the environment is considered to be non-invasive. Ideally the electric motor would run on single phase mains electric supply although for the purpose of designing and implementing a prototype system, a three phase connection was considered as acceptable. Given the proposed figures for speed, S, and torque, τ, the maximum power requirements, P, of the system could be calculated as follows:

$$P = S \times \tau \tag{4.1}$$

$$\therefore P = 350 \times (500/360) \times 2\pi = 3054\ W \tag{4.2}$$

Given normal mains voltage, V, 230 V, 50 Hz frequency, and nominal supply current, I, of 13 A. The power available from the mains can be calculated using the following formula:

$$P = I \times V \tag{4.3}$$

$$\therefore \mathrm{P} = 13 \times 230 = 2990\ \mathrm{W} \tag{4.4}$$

Note: Although these calculations indicate that a single phase mains supply is not quite capable of providing the maximum required amount of power (and therefore the electric motor in this research was operated from a three phase source) these calculations assume: (i) steady state conditions and it is unlikely that athletes will be able to maintain this level of output for extended periods and (ii) the operator is capable of elite performance which is unlikely to be the case for the general user.

Following a brief investigation of the fundamental motor types as identified in Figure 4.3, direct drive systems were initially identified as the most appropriate solution for the primary input source. Characterised by their relatively short overall length and large outer diameter, this configuration is designed to offer improved accuracy and dynamic performance. The main advantages of using a direct drive system are the elimination of additional rotary power transmission elements and therefore efficiency is maximised.

The main disadvantage when using an electric motor such as this is the high purchase cost. Specialist, high precision direct drive units may cost up to a factor of 10 times more then a standard motor. The physical dimensions of these motors (typically 0.2 m-1 m in diameter) could result in additional design constraints and the overall weight could limit movement of the unit once installation is complete. On the other hand, stability is enhanced by designing a large mass with a low centre of gravity into the system.

The practical restrictions of using a direct drive solution lead to an in depth review of conventional electric motor units. Synchronous AC servo motors were identified based upon their abilities to proved highly dynamic performance with excellent speed and torque control. These units are widely used in many different applications and feature the key characteristics required for this particular rotary power transmission (Gottlieb, 1997). Relatively small performance variations were identified between equivalent product solutions available from commercial suppliers of synchronous servo motors. Final selection was made based upon supplier knowledge, unit cost, technical support, industrial reputation and system integration capabilities (e.g. connection to external control elements and hardware components).

The maximum torque capabilities of AC synchronous servomotors (e.g. 1 Nm- 250 Nm) are relatively small in comparison to direct drive systems (e.g. 175 Nm – 7500 Nm). In order to achieve the desired performance levels, some form of gear reduction or pulley system was required. This modifier unit scales the magnitude of torque and speed inputs from the primary drive source and provides an output which exhibits the desired performance levels (see section 4.2.1.2 below).

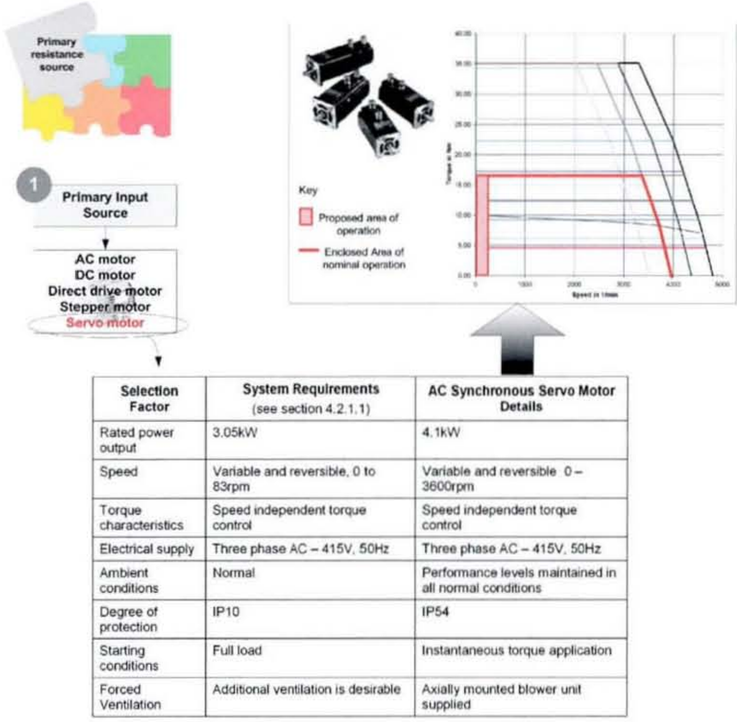
The quantitative requirements outlined in Chapter 2 and information presented in the product design specification was utilised in order to specify the most effective solution. The main selection criteria used to asses the potential solutions together with the performance characteristics of the synchronous motor that was eventually chosen are detailed in Figure 4.4. Additional technical information regarding the primary drive source is shown in Table 4.1.

Parameter	AC Synchronous Servo Motor Technical Data
Rated torque	11.0 Nm
Rated current	9.2 A
Peak torque	35.2 Nm
Peak current	32 A
Polar moment of inertia	8.0×10^{-4} kgm^2
Size (l*w*h)	362 * 130 * 130 mm
Weight	12.2 kg

Table 4.1: Additional technical details of the AC synchronous servo motor.

The preferred solution utilises a stock servo motor which provides the necessary dynamic performance capabilities with independent torque and speed control in a relatively small operational envelope and at relatively low cost. Driven by a three-phase supply, this unit is capable of instantaneous torque application and allows rapid direction changes which are necessary during isokinetic exercise routines. Current demands during normal operation are acceptable and unit weight is minimal compared to direct drive systems.

The combinations of torque and speed at which the AC synchronous servo motor can operate can be represented graphically as shown in Figure 4.4. The maximum torque output is determined by the particular servo drive selected (see section 4.7). The red line shown in Figure 4.4 represents the maximum torque and speed capabilities of the motor and drive system selected for this application. The shaded area represents the basic drive requirements as outlined in the specification. Using the proposed motor and servo drive combination it is clear that the desired performance characteristics are within the operational limits of the system.



Selection Factor	System Requirements (see section 4.2.1.1)	AC Synchronous Servo Motor Details
Rated power output	3.05kW	4.1kW
Speed	Variable and reversible, 0 to 83rpm	Variable and reversible 0 – 3600rpm
Torque characteristics	Speed independent torque control	Speed independent torque control
Electrical supply	Three phase AC – 415V, 50Hz	Three phase AC – 415V, 50Hz
Ambient conditions	Normal	Performance levels maintained in all normal conditions
Degree of protection	IP10	IP54
Starting conditions	Full load	Instantaneous torque application
Forced Ventilation	Additional ventilation is desirable	Axially mounted blower unit supplied

Figure 4.4: Selection and key operational data of the preferred primary input source.

4.2.1.2 Power modifier selection

As discussed in section 4.2.1.1, the relatively low output torque produced by the AC synchronous servo motor needed to be converted in order to fully satisfy the design requirements. A number of influential factors were considered when selecting a suitable power modifier as shown in Figure 4.5. The system would need to operate bi-directionally and therefore the unit must be reversible. The final arrangement should be space and cost effective whilst maintaining reliability. The unit must be capable of withstanding the maximum output torque (350 Nm) and speeds defined in Chapter 2 and introduce minimal losses to the transmission system. Given that the nominal output torque of the motor was 11.0 Nm, the drive ratio required was calculated as follows:

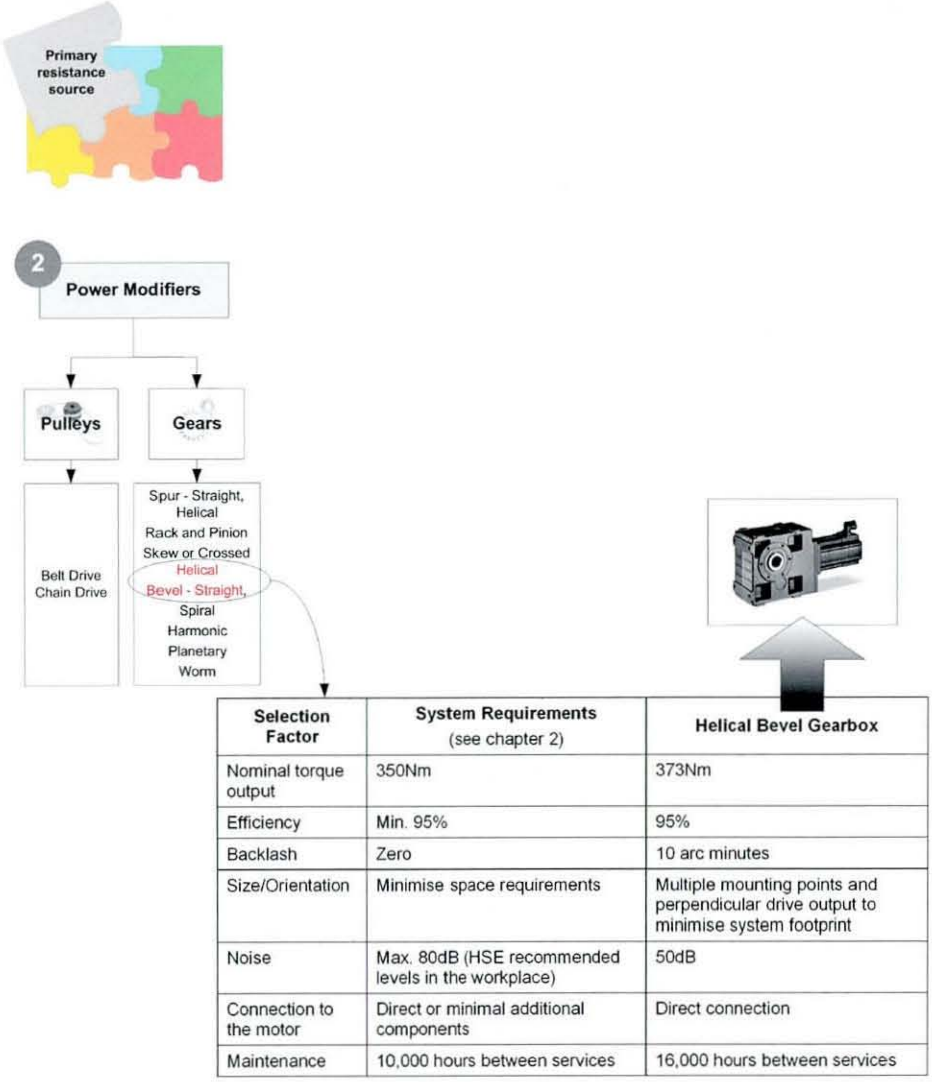
$$\text{Drive Ratio} = \frac{\text{Required output torque}}{\text{Supplied input torque}} = \frac{350}{11} = 31.8 \qquad (4.5)$$

$\therefore$ Minimum drive ratio for producing the maximum required torque $= 32$

Upon initial investigation it appeared that a pulley and belt driven power modification system would be well suited to this application. Low noise emissions, self lubrication and relatively low cost were the main desirable attributes of such an arrangement. A toothed belt and pulley would be required in order to maintain the positional accuracy of the system and the commercial products identified could easily accommodate the maximum power output calculated.

Although there were a number of desirable features with using a pulley system this approach was not developed due to the practical implications of producing the desired drive ratio. A single stage reduction of this magnitude is not common in normal applications and therefore it was determined that a multi-stage array would be required (Hamilton, 1997). Additional stages would increase cost and complexity whilst reducing efficiency, therefore the distributed approach of a pulley system was considered unsuitable for this application.

Gears provide an opportunity for achieving much higher drive ratios then pulleys at greater levels of efficiency and accuracy (Vogwell, 1997). The additional cost, noise, weight and maintenance penalties associated with this form of power modification system were considered acceptable given the associated performance gains. An important factor in the selection of a geared system was the minimisation of inherent backlash in the unit which could reduce the level of output control and introduce undesirable operational characteristics which could be felt by the user.



Selection Factor	System Requirements (see chapter 2)	Helical Bevel Gearbox
Nominal torque output	350Nm	373Nm
Efficiency	Min. 95%	95%
Backlash	Zero	10 arc minutes
Size/Orientation	Minimise space requirements	Multiple mounting points and perpendicular drive output to minimise system footprint
Noise	Max. 80dB (HSE recommended levels in the workplace)	50dB
Connection to the motor	Direct or minimal additional components	Direct connection
Maintenance	10,000 hours between services	16,000 hours between services

Figure 4.5: Selection and key operational data of the preferred power modifier.

Harmonic and planetary drives were identified as potential solutions due to their ability to produce high reduction ratios in a single stage, often with zero gear backlash, and can be driven backwards (Hamilton, 1997). Harmonic drives provide zero backlash capabilities but suffer from relatively poor efficiency and also create torque / speed anomalies during constant operational conditions. Planetary systems offer improved efficiency and smooth running but will introduce a quantifiable level of backlash into the system. Both of these approaches offer acceptable performance characteristics but the commercial cost of each item was sufficient to justify the investigation of multi-stage simple geared systems as a viable alternative to these complex single stage units.

A range of multi-stage gearboxes developed specifically for use with the primary power source were identified and analysed. Using existing industrial selection methodologies (e.g. selection matrices), a right angled helical bevel gearbox was selected to provide power modification in the exercise system. This configuration features dual outputs which ensured maximum design freedom and provided the opportunity for additional functionality to be incorporated into the final embodiment. Using the manufacturers recommended guidelines, the gearbox selected was a self encased unit utilising 3 stages to create an overall reduction ratio of 34:1. The basic technical data for the gearbox is given in Figure 4.5.

4.2.1.3 Actuator selection

Many of the existing isokinetic dynamometers and resistance training systems discussed in Chapter 2 utilise an actuator in the power transmission system to create the desired speed and torque characteristics from relatively simple drive arrangements. The particular type of actuator varies according to the other components in the system but will fundamentally consist of some form of braking system or a clutch type mechanism as listed in Figure 4.6. Advances in clutch and brake technology have lead to improvements in performance and reliability but have been accompanied with considerable increases in cost. By combining the synchronous servo motor with a suitable servo drive unit it is possible to achieve the required motion without the need for these auxiliary power transmission elements.

Careful control of system motion parameters, such as torque and velocity, during initiation, operation and at termination can be achieved with modern servo systems. The static hold capabilities of the servo and drive arrangement are limited by the maximum supply current and the heat dissipation capacity of the motor. Given the predicted load conditions experienced during an isometric exercise (see Chapter 2), the servo system specified would provide sufficient static torque (i.e. nominally 373 Nm) to satisfy the requirements without an additional brake unit.

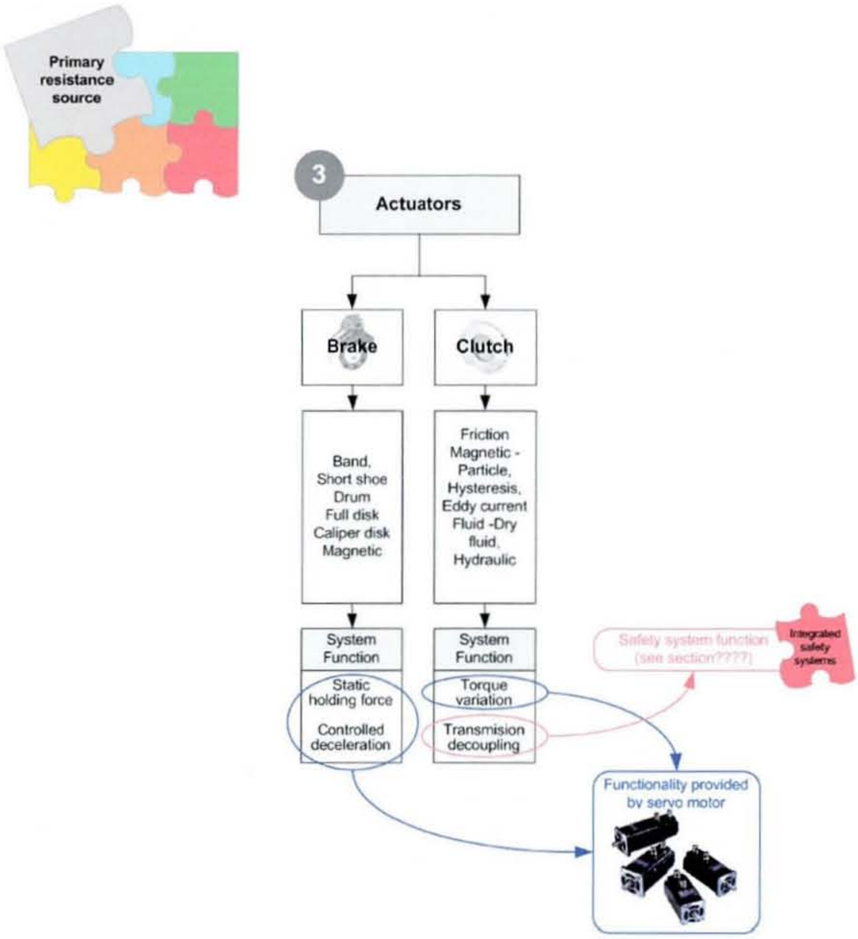
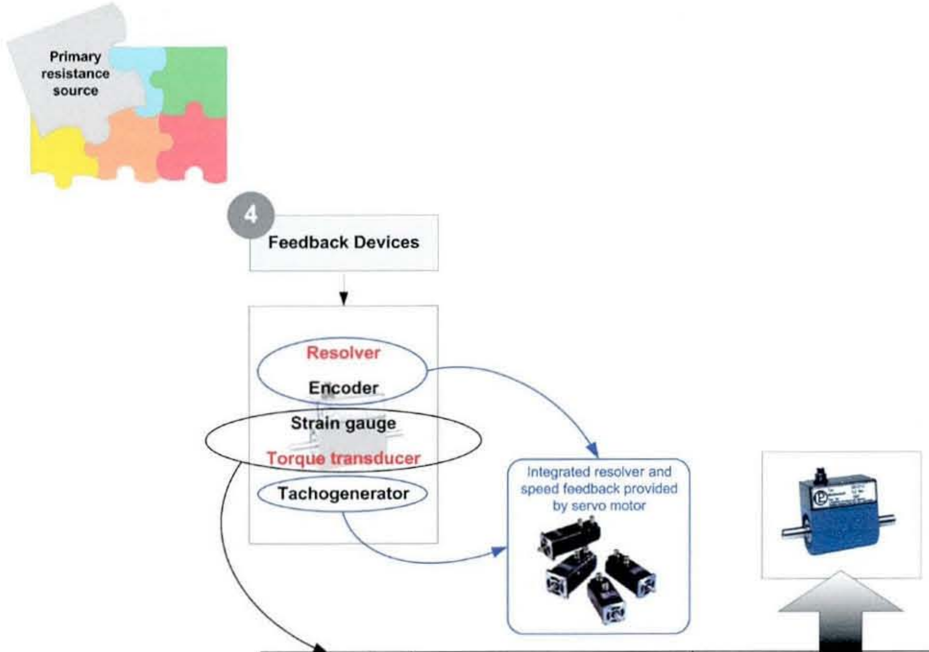


Figure 4.6: Identification of actuator functionality and common functions provided by servo motor systems.

In industrial rotary power transmission applications, clutch systems are commonly used as integral safety devices to protect sensitive machine components. The clutch is configured to disengage at a predefined torque level in the event of a malfunction and thus prevents further load from being applied to the output. The unit will continue to apply the limiting load until the drive input is reduced. This torque limiting property during failure can be considered unsuitable for a system with direct human-machine interactions where there is the potential for trapping and other hazards. In this case, if a fault occurs with the exercise system, the load applied to the user must be completely removed until the problem is resolved.

4.2.1.4 Selection of system feedback devices

In order to achieve the desired level of motion control, a number of additional transmission elements were required to provide feedback signals to the servo drive (see Figure 4.7). These items record real time quantitative data regarding key movement parameters and allow the exact characteristics of each to be monitored and altered according to the applied input.



Selection Factor	System Requirements See Chapter 2	Lorenz Contactless Torque Transducer
Torque capacity	350Nm	500 Nm
Accuracy	Min. 0.1%	0.1%
Repeatability	Max. +/- 0.05%	+/- 0.02%
Output signal	Digital or analogue	+/- 10V
Sample rate	2kHz	10kHz
Protection	IP20	IP50
Mechanical Integration	Direct or minimal additional components	Supplied with plain input/output shaft for connection via shrink fit couplings

Figure 4.7: Servo motor integral feedback systems and selection of a torque feedback device.

4.2.1.4.1 Position feedback device

Positional information is critical in the operation of any servo system. These signals are the fundamental measurements from which other variables, (e.g. velocity, acceleration) can be established and are key input parameters in the simulation of the exercise routines identified in Chapter 1.

There are two main devices commonly used for recording position: encoders or resolvers. Encoders are generally supplied as discrete high accuracy units for insertion into the transmission system. Absolute encoders provide accurate feedback information (around ± 0.8 arcminutes) regarding the position of the unit, maintain position signals during power cycling and are suitable for a wide range of speed applications but can be costly.

Alternatively, many manufacturers supply servo motors with integrated resolvers as standard. Resolvers are robust and durable units with positional accuracies of approximately ± 10 arcminutes and resolutions around of 0.8 arcminutes. This level of performance has been deemed as acceptable for resistance systems in clinical and research environments (Drouin *et al.*, 2004). Therefore, it was decided that the integrated brushless pancake design resolver offered by the preferred motor supplier would be the most suitable positional device for this application.

4.2.1.4.2 Torque feedback device

Accurate control of the torque in a complete servo system utilises the error between the actual torque produced at the output and the required set point to make appropriate adjustments to the primary drive source. By forming a closed feedback loop in this manner, system stability can be maintained and the resultant torque in the transmission system can be closely regulated. There is a vast number of alternative technologies that could be used for measuring torque which vary according to cost, accuracy, repeatability and resolution.

Following an initial investigation of potential torque feedback technologies it was decided that the most effective solution for this transmission would be a modular torque transducer unit. These systems are self contained measurement units which can be inserted directly into an existing drive. A high level of accuracy is assured and the necessary signal modifications are conducted within the unit. Although the initial cost of a torque transducer unit was high in comparison with other approaches (e.g. strain gauges), the additional costs incurred could be offset against the projected time and resource requirements of developing, calibrating and implementing a customised device.

Using a dedicated transducer, the measured output torque is transformed into a simple linear analog output which can be feed into any number of different input devices. Final selection of a commercial unit was based upon the results of a performance, reliability and output matrix as shown in Figure 4.7. Transducer accuracy (± 0.008 degrees) was considered to be the primary selection criteria as this would be valuable for future testing and system performance analysis although this was carefully considered against individual component cost. A multi-turn, non-contact unit was specified as the unit would be required to operate under continuous revolutions as encountered during an aerobic exercise. The measurement capabilities of the transducer have been specified to correspond with the magnitude of the maximum torque output (i.e. maximum output 500 Nm) from the gearbox to ensure precise system control and accurate data readings.

4.2.1.4.3 Velocity feedback device

In order to provide closed loop velocity control for movements such as those expected during an isokinetic exercise, some form of speed feedback was required. This information could be extrapolated from encoder position data to provide a basic measure. However, for velocity critical applications, tachogenerators are available which provide advanced levels of accuracy particularly at high velocities. The synchronous servo motor and drive combination detailed in sections 4.2.1.1 and 4.7 features a velocity feedback system using the integrated resolver. Given the magnitude of operational velocities and dynamic variations defined in Chapter 2 are relatively low, the integral resolver feedback was considered as sufficient for providing velocity feedback in this arrangement.

4.2.1.5 Couplings selection

Having defined the major rotary power transmission elements the relevant coupling systems could then be identified. Figure 4.8 is a diagrammatic representation of the physical components of the drive system as discussed in sections 4.1.2.1 to 4.1.2.5. The individual elements must be connected using the coupling systems identified in a sequential manner in order to create a complete assembly. The coupling systems were selected according to their performance, geometry, safety, maintenance, reliability and availability.

There are two main coupling mechanisms: flexible and rigid. Rigid couplings consist of solid or hollow shafts which form a fixed connection between adjoining elements. Flexible couplings compensate for any misalignment between the central connection axis of each element and can also be specified with a predetermined level of torsional flexibility. For a servo system such as that discussed in this investigation, any torsional flex or loss of power through the transmission is regarded as undesirable as this decreases efficiency, increases control requirements and can result in system instability.

Each connection (i.e. A, B and C in Figure 4.8) was assessed on an individual basis to ensure that the most effective solution was developed. The connection between the primary drive source and the gearbox, connection A in Figure 4.8, was made via a rigid coupling. The manufacturer supplied the two units pre-assembled such that the pinion gear is pressed directly onto the output shaft of the motor. Connection B as shown in detail in Figure 4.8, links the output of the gearbox with input of the torque transducer. A rigid shaft clamped through the gearbox provides the initial drive transfer which is then attached to the transducer. The transducer unit is a floating system and therefore can be attached directly to the gearbox using a rigid coupling without misalignment concerns.

The technical specifications of this rigid coupling were determined by the external diameter of the gearbox shaft, transducer input and maximum torque defined in Chapter 2. The gearbox shrink fit connection system required the specification of a solid output shaft to prevent crushing during fitment. Assuming that a shaft of low grade steel material was used under pure torsional stress, the minimum safe diameter for this element, including the necessary factors of safety, n, could be calculated.

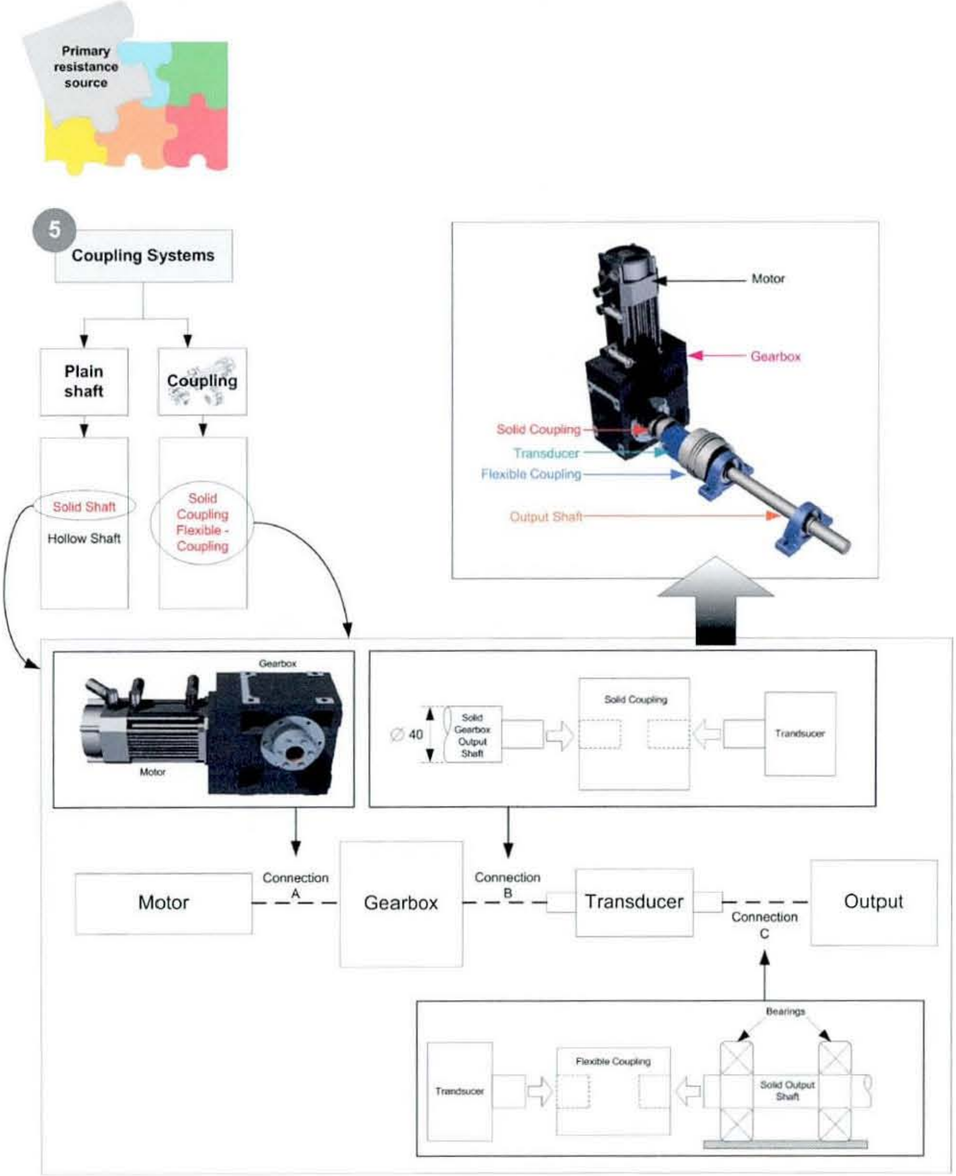


Figure 4.8: Coupling selection for power transfer from the primary resistance system to the output.

In the interests of ensuring absolute user safety, it was envisioned that if the system were ever to become unstable and accelerate to full torque / speed, it will be prevented from continuously rotating by a set of physical limit stops (see section 4.6.3). In this scenario, the transmission will be loaded in a heavy shock condition (b = 2.0 –3.0) as the drive will experience an almost instantaneous retardation. The inclusion of a torque limiting device should minimise the occurrences of a loading condition such as this and therefore a value of 2.0 was selected for load shock factor b.

Basic EN3 steel was selected for these initial calculations which would represent the minimum quality manufacturing specifications that could be used. This relatively ductile material should have a uniform microstructure (c = 1.5-1.75). The properties used were generic values as defined by the relevant standards. Due to a lack of specific information, a value c = 1.75 was used to compensate for the deficit in precise material knowledge.

$$\text{Factor of safety, } n = b \times c \tag{4.6}$$

$$\therefore \quad \text{Factor of safety, } n = 2.0 \times 1.75 = 3.5 \tag{4.7}$$

Using the basic properties of steel, shear strength, τ = 350MPa

$$\therefore \quad \text{Design stress, } \tau_{allow} = \frac{\text{stress at failure}}{\text{factor of safety}} = \frac{350 \times 10^6}{3.5} = 100MPa \tag{4.8}$$

Shear stress due to torsion, τ, for a solid shaft is given as follows

$$\tau = \frac{16T}{\pi d^3} \tag{4.8}$$

The formula above can be rearranged to determine the minimum outer diameter of the shaft;

$$d = 1.72 \times \sqrt[3]{\frac{T_{\max}}{\tau_{\max}}}$$

$$d = 1.72 \times \sqrt[3]{\frac{373}{100 \times 10^6}} \tag{4.9}$$

$$d = 0.032m$$

$\therefore$ The minimum shaft diameter required to resist the predicted torsional load = 32mm.

The outer diameter of the torque transducer input shaft was 32 mm, thus in order to reduce the cost of the rigid coupling, the output shaft was designed to include a step from the 40mm inner diameter of the gearbox to 32 mm to suit the transducer. This value exceeds the minimum diameter calculated previously and therefore would provide an additional safety factor during operation. The angular deflection of the shaft (θ_S) at maximum torque can be calculated as follows:

$$\theta_S = \frac{TL}{GJ} \tag{4.10}$$

The second polar moment of area J for a solid shaft is:

$$J = \frac{\pi d^4}{32} \tag{4.11}$$

$$J = \frac{\pi \times 0.02^4}{32} = 2.51 \times 10^{-7} m^4 \tag{4.12}$$

Therefore the shaft angular deflection will be:

$$\therefore \theta_S = \frac{148 \times 0.15}{79 \times 10^9 \times 2.51 \times 10^{-7}} \tag{4.13}$$

$$\theta_S = 1.12 \times 10^{-3} rads = 0.064^o$$

Connection C in Figure 4.8 forms the link between the output shaft of the transducer and the final actuator. In order to support the load applied by the actuator this connection required some form of support. A simple mechanical bearing arrangement was proposed which would provide the required load platform.

Given that the predicted forces applied to this connection were identical to those at connection A, the outer diameter of this shaft was designed to that match that of the transducer. Axial load was considered to be negligible assuming that all exercises would be conducted in a rotation about a horizontal axis. Initial specification of the bearings was based upon the inner diameter required to the suit the actuator shaft. Radial bearing loads and actuator shaft twist could not be calculated until the physical geometry of the system was finalised in later stages of the development process (see section 4.7).

This actuator shaft section required some form of connection to the plain output shaft of the torque transducer (connection C, in Figure 4.8). A flexible coupling unit was incorporated into the design to compensate for any manufacturing tolerance build-up, shaft deflection, vibrations and wear in the rotary power transmission components.

The array of potential flexible coupling systems was reduced systematically to a single suitable solution using knowledge of the maximum operational torque (373 Nm), high torsional stiffness ($> 500 \times 10^3$ Nm/rad) and low inertia requirements ($< 7 \times 10^{-3}$ kgm^2). The metal bellows coupling selected, provided the necessary range of torque and speed capabilities (i.e. 500 Nm and 10,000 rpm respectively) and featured conical compression sleeves for direct attachment to the drive shafts with no backlash.

A CAD visualisation of the configuration of the electrical resistance source elements is shown in Figure 4.8. The orientation depicted in this image gives the assembly a relatively low centre of gravity, thereby adding stability to the overall system, whilst minimising the spatial footprint. The combination of an AC synchronous servo motor system and separate torque transducer fulfil the control and performance requirements that were identified in the design specification. A complete rotary power transmission was developed around these elements to produce a core resistance system around which the remaining sub-systems could be constructed.

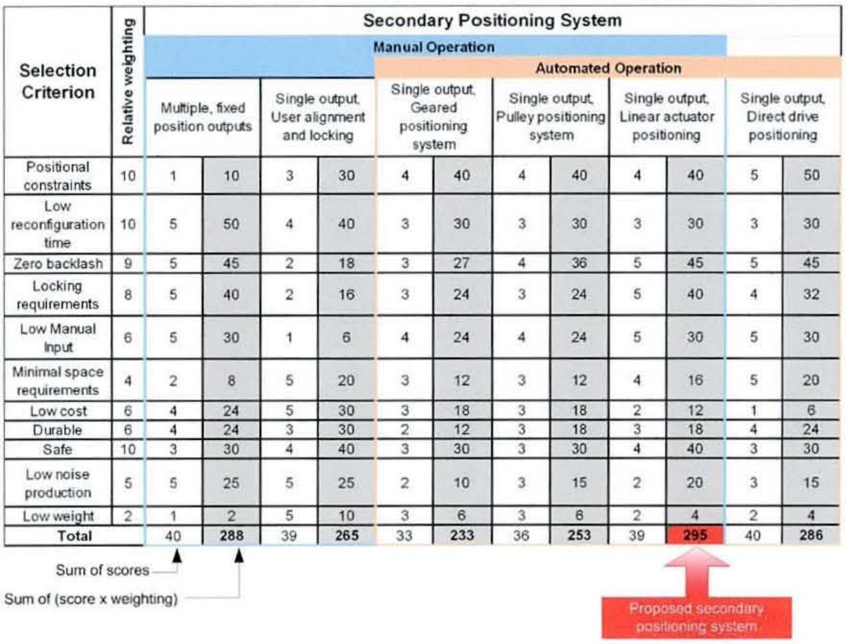
4.3 Development of the secondary positioning system

Following the specification of a primary resistance source, a method for providing multi-joint exercise capabilities from this single output was required (see Chapter 2). Adjustment of the resistance output location to correspond to the axis of rotation of different joint positions was intended to be an initiative process and accommodate as wide a range of exercises as possible. In each operational position, the system must maintain a high level of stability and reconfiguration time should be minimised.

A concept generation process was undertaken to produce an unconstrained range of solutions. This collection of unrefined ideas was screened to remove those concepts which were identified as acutely impractical or unsuitable. The remaining designs were organised into the evaluation matrix shown in Figure 4.9. Analysis of the initial concepts resulted in the creation of two main groupings. A reconfigurable output could be achieved using manual inputs or via an automated system. The post-screening designs included those concepts which were purely manual or purely autonomous but also featured an overlapping set of ideas which could utilise manual or powered inputs to achieve the same result.

Selection criterion were extracted from relevant aspects of the design specification and assigned a weighting (0-10, a weighting of 10 indicates an essential design parameter) based upon the relative importance of each factor. Each concept was assessed using the selection criteria and awarded a grade (0-5, a value of 5 represents a strong level of coherence with the criteria) depending upon its ability to conform to the requirements. The sum of these scores was used as a quantitative assessment method to identify the design which would, conceptually, provided the desired system features.

As indicated in Figure 4.9, analysis of the evaluation matrix results indicated that a single output system using a linear actuator for altering positioning produced the highest overall rating. This solution was awarded strong ratings in the essential selection criteria (e.g. reconfiguration time, safety and low backlash) but also received good ratings overall and therefore were selected as the main concept for further development.



Selection Criterion	Relative weighting	Secondary Positioning System											
		Manual Operation											
						Automated Operation							
		Multiple, fixed position outputs		Single output, User alignment and locking		Single output, Geared positioning system		Single output, Pulley positioning system		Single output, Linear actuator positioning		Single output, Direct drive positioning	
Positional constraints	10	1	10	3	30	4	40	4	40	4	40	5	50
Low reconfiguration time	10	5	50	4	40	3	30	3	30	3	30	3	30
Zero backlash	9	5	45	2	18	3	27	4	36	5	45	5	45
Locking requirements	8	5	40	2	16	3	24	3	24	5	40	4	32
Low Manual Input	6	5	30	1	6	4	24	4	24	5	30	5	30
Minimal space requirements	4	2	8	5	20	3	12	3	12	4	16	5	20
Low cost	6	4	24	5	30	3	18	3	18	2	12	1	6
Durable	6	4	24	3	30	2	12	3	18	3	18	4	24
Safe	10	3	30	4	40	3	30	3	30	4	40	3	30
Low noise production	5	5	25	5	25	2	10	3	15	2	20	3	15
Low weight	2	1	2	5	10	3	6	3	6	2	4	2	4
Total		40	**288**	39	**265**	33	**233**	36	**253**	39	**295**	40	**286**

Sum of scores

Sum of (score x weighting)

Proposed secondary positioning system

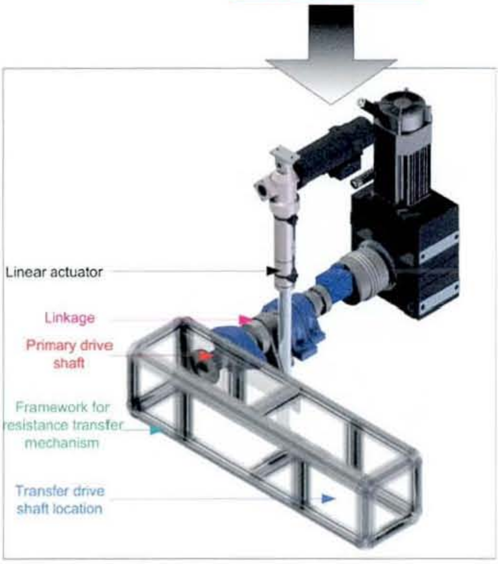


Figure 4.9: Quantitative analysis of potential secondary positioning systems against key selection criteria.

This linear actuator system concept uses a cam mechanism to produce rotary motion around a fixed axis. It was envisioned that this cam would be fixed to an independent framework. This framework houses an additional drive system which transfers the primary resistance to a secondary output location along its length. Activation of the linear actuator, causes the framework to rotate due to the mechanical action of the cam. The change in angular position results in a vertical displacement which can be adjusted to suit the required joint position. The physical properties of a linear actuator would also allow the specification of a relatively small motor and provide resistance against back driving once the system was in position and operational.

4.3.1 Detailed design of the positioning system elements

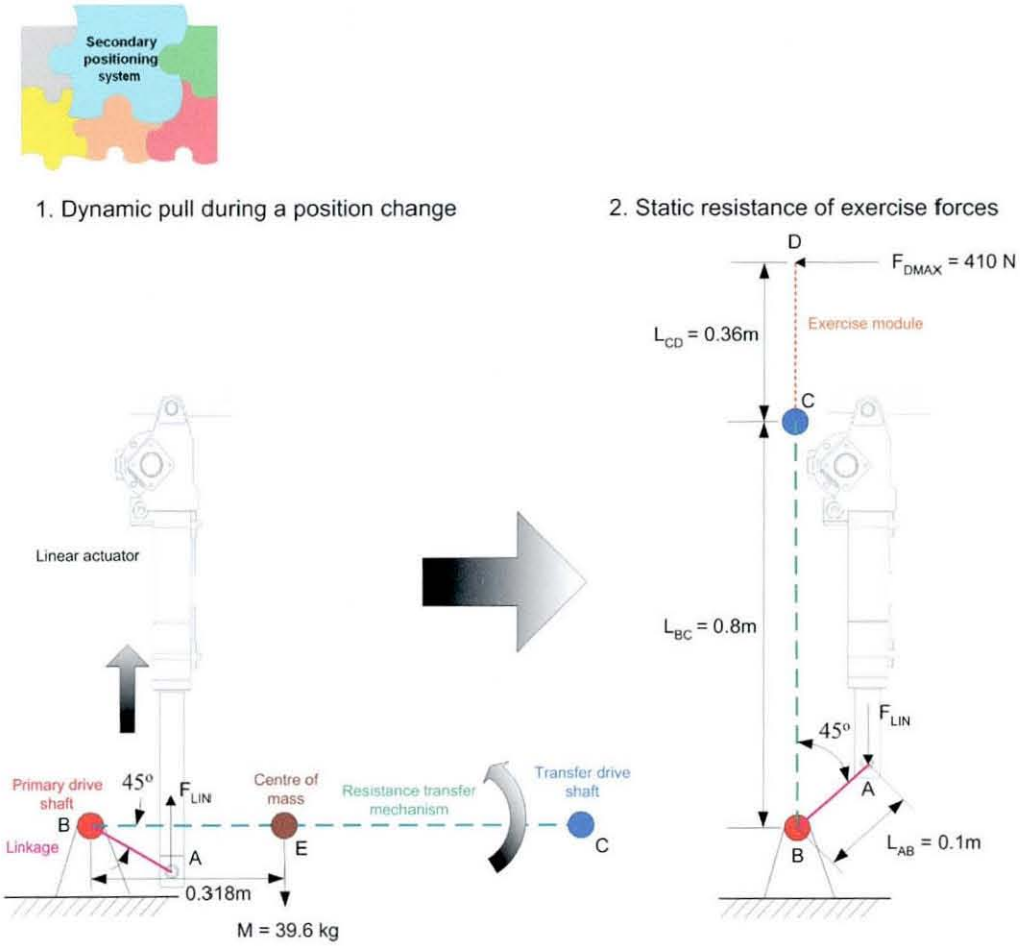
In order to minimise overall size, the linear actuator was initially designed to operate in a vertical position as indicated in Figure 4.10. A cam mechanism was designed to suit the basic dimensions of the primary resistance source and connection requirements. Following a review of the primary exercises identified in Chapter 2, it was established that the transfer framework would only need to rotate through a 90-degree arc from a horizontal datum. Allowing the framework to rotate beyond this point would simply result in the replication of vertical displacements encountered during the first quadrant of movement. Therefore, the cam and linear actuator could be readily arranged to suit this limited range of motion.

The location of the resistance output will only be altered after each mode of exercise has been completed. Therefore the linear actuator will only be operating in a low duty cycle suited to ACME screw thread systems. These low cost mechanisms feature a statically irreversible nut which prevents the load driving back through the actuator and hence modifying the load position. Commercial actuators are supplied with proximity switches to provide simple position control. However, the switching band (i.e. 17mm) makes them unsuitable for applications which require multiple operational positions within a short working stroke. Therefore, a servo motor and drive would be necessary to power the actuator and provide the positional resolution from the proposed arrangement. By specifying a servo motor and drive system, the angular velocity of the framework could also be adjusted post assembly to satisfy any safety standards and user requirements for controlled speed of positional adjustment.

Final selection of the actuator and servo motor could not be completed until the physical details of the system were finalised (see section 4.7). The critical loading conditions which were used to specify the linear actuator and motor combination are illustrated in Figure 4.10. Case 1 in Figure 4.10 represents the maximum dynamic pull force required to raise the transfer framework from a horizontal position. The centre of mass of the transfer arm was calculated using Solid Edge V18 CAD modelling software. Information regarding individual component masses was combined with theoretical weights for fabricated items calculated in Solid Edge using knowledge of the material densities and part geometries. The resultant mass and overall centre of gravity could then be determined about a relevant point.

In loading case 1, the axis of rotation of the transfer arm was considered as the main pin support about which the resultant forces could be resolved. With the transfer arm in the lowered position, the cam mechanism will be aligned at 45 degrees as shown in Figure 4.10, diagram 1. In this orientation the system is configured for an aerobic exercise. Using the values determined in Solid Edge, the resultant pull force required from the actuator to raise the transfer arm was calculated as 1747 N.

Case 2 in Figure 4.10 shows the transfer arm in the full raised position with the cam mechanism at 45 degrees above the horizontal datum. In this orientation the system is configured for an arm curl exercise with the attachment aligned to maximise the applied bending moment. Given that maximum torque is applied through the resistance system a resultant force can be determined at the contact point of the exercise attachment. If this force is applied to the attachment during a static isometric exercise, assuming no slipping occurs in the primary resistance system, the bending moment will be transferred through the framework and cam mechanism into the linear actuator. By resolving moments about the secondary positioning system's axis of rotation the static load upon the actuator was determined to be 6727 N.



Moments about point B

$$F_{LIN} \times (\sin\theta \times L_{AB}) = Mg \times L_{BE}$$

$$F_{LIN} = \frac{Mg \times L_{BE}}{\sin\theta \times L_{AB}} = \frac{(39.6 \times 9.81) \times 0.318}{\sin 45 \times 0.1}$$

$$F_{LIN} = 1747N$$

Given that the maximum dynamic pull force of the proposed linear actuator is 2800N, this mechanism will be suitable for the secondary positioning system

Moments about point B

$$F_{LIN} \times (\sin\theta \times L_{AB}) = F_{DMAX} \times L_{BD}$$

$$F_{LIN} = \frac{F_{DMAX} \times L_{BD}}{\sin\theta \times L_{AB}} = \frac{410 \times 1.16}{\sin 45 \times 0.1}$$

$$F_{LIN} = 6727N$$

Given that the maximum static push force of the proposed linear actuator is 10000N, this mechanism will be suitable for the secondary positioning system.

Figure 4.10: Mechanical load analysis of the secondary positioning system drive mechanism.

Using these figures, a simple selection procedure could be conducted to identify a suitable linear actuator (i.e. Servomech BSA30) from those commercially available. The required stroke length (i.e. 150 mm) was calculated using basic trigonometry and mounting points / bracing specified accordingly.

4.4 Selection of a resistance transfer mechanism

The output of the primary resistance system was designed to pass directly through the axis of rotation of the secondary positioning system into the transfer arm. A mechanism was required to translate the drive along the length of the transfer arm to an appropriate output point. A review of power transfer mechanisms was conducted to identify potential solutions to the design problem. The range of products available was systematically reduced until a suitable group was formed and organised into a quantitative evaluation matrix.

Each design was assessed against a weighted series of selection criteria using an identical methodology as discussed previously (sections 4.2 and 4.3). The ability of each mechanism to satisfy significant criteria was evaluated together with an assessment of its overall suitability to determine subjectively a design for further development. As indicated in Figure 4.11 a pulley and belt system was found to have the highest overall score. Such systems could provide a high efficiency, low inertia system that would ensure maximum power was transmitted to the secondary output without significant losses and unnecessary complexity. Constant power transmission, low backlash and minimal noise production were also beneficial characteristics exhibited by pulley and belt systems.

Further investigation into belt and pulley technologies resulted in the specification of a timing belt / pulley combination. A toothed system provides zero backlash and accommodates the transfer of higher torques such as those produced by the primary resistance system. Pulley diameters were selected based upon the minimum recommended size permitted for the specified power and configured with a 1:1 ratio. This solution provided a simple and effective method for transferring the output torque which could be incorporated into the transfer framework with minimal design implications as shown in the CAD illustration in Figure 4.11.

Selection Criterion	Relative weighting	Resistance transfer mechanisms									
		 Pulley and belt drive		 Shaft drive		 Chain drive		 Hydraulic drive		 Crank rocker linkage	
High efficiency	10	5	50	5	50	4	40	4	40	4	40
Low inertia	8	4	32	3	24	3	24	3	24	2	16
Zero backlash	9	5	45	4	36	3	27	2	18	5	45
Consistant power transmission	10	4	40	5	50	4	40	4	40	2	20
Minimal space requirements	4	3	12	5	20	3	12	3	12	2	8
Low cost	6	4	24	5	30	4	24	2	12	4	24
Durable	6	4	24	4	24	3	18	3	18	3	18
Safe	10	4	40	4	40	3	30	2	20	4	40
Low noise production	7	5	35	2	14	2	14	4	28	3	21
Low weight	2	4	8	3	6	3	6	2	4	2	4
Total		42	**310**	40	**294**	32	**235**	29	**216**	31	**236**

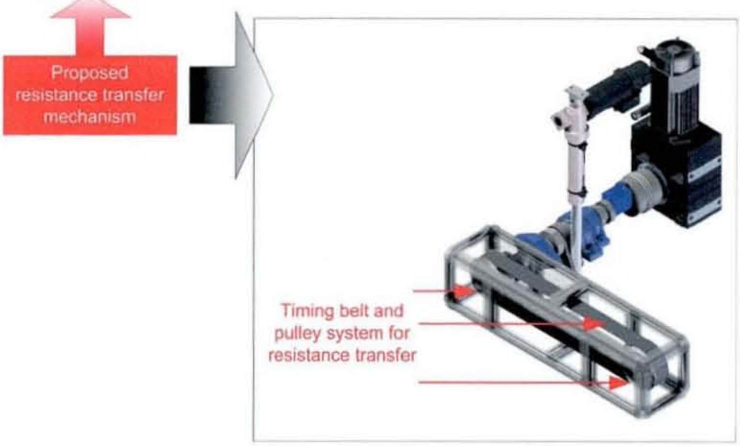


Figure 4.11: Quantitative analysis of resistance transfer mechanisms against key selection criteria.

4.5 Development of an exercise module attachment method

As discussed in Chapter 2, the overall system was required to provide the facility for attachment of different exercise actuators that could be easily interchanged. A method for attaching these various exercise modules to the primary rotary transmission would need to be developed. Using a relevant sub-set of requirements established from the design specification, important design attributes were identified to provide focus during the initial development phase.

Research into temporary connection systems lead to the creation of a diverse range of design concepts. The requirements and an example of these designs are shown in Figure 4.12. A critical review of these ideas resulted in the omission of many of the suggestions due to practicality, suitability and feasibility concerns. This qualitative analysis resulted in the identification of a single concept which would provide the required performance and design features (e.g. low backlash, consistent power transmission and high efficiency) whilst being simple to operate.

Figure 4.12 includes a CAD illustration of the solution embodiment. This assembly was created through an iterative development process during which the individual component geometries, materials, connections / interactions and functions were explored and enhanced. The final product was a compact, modular solution which could be easily integrated into the proposed transfer framework.

The exercise module attachment system consists of three core design elements as shown in Figure 4.12. Each exercise attachment incorporates a splined steel shaft and bearing assembly. The splined shaft locates in a bronze hub which is directly connected to the upper pulley of the resistance transfer mechanism. This arrangement ensures that the power transmission is as efficient as possible with minimal backlash. The materials specified for the shaft and hub should be durable but also provide a small level of natural lubrication to aid insertion / removal.

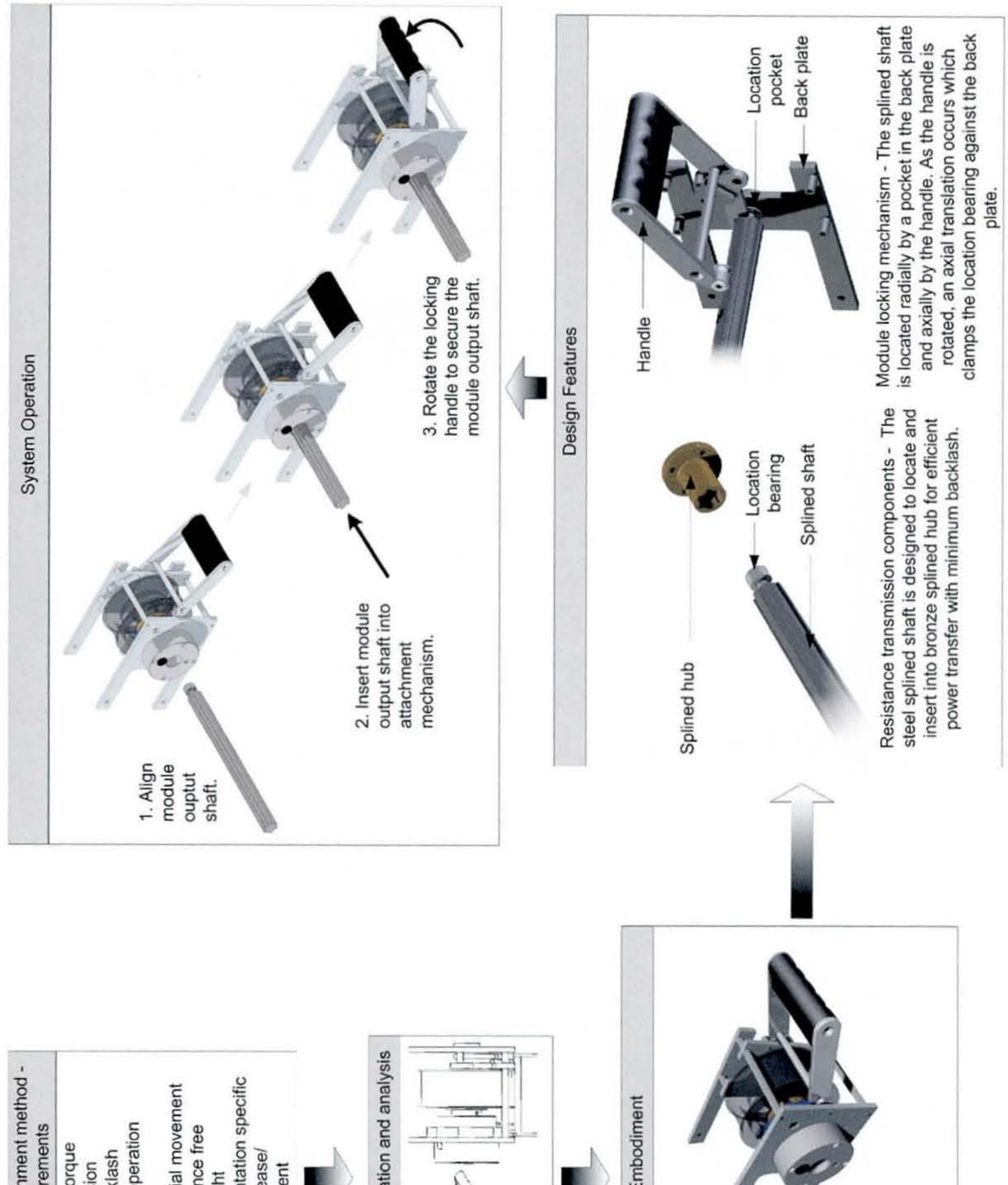


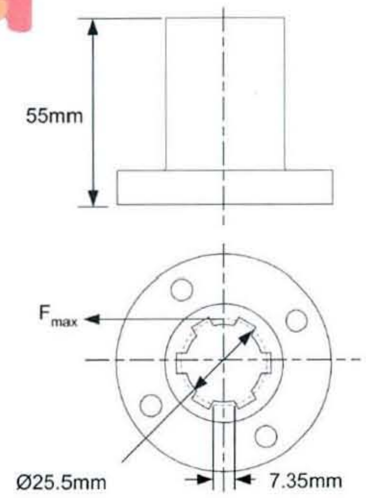
Figure 4.12: Illustration of the development process and operational features of the module attachment system.

The bearing assembly found at the end of each module attachment shaft is designed to resist any axial movement that may be imparted by the user. Upon insertion, this unit passes through the splined hub and locates radially in a precision pocket machined in the back plate of the attachment assembly. This pocket is designed to act as an insertion limit which ensures that the shaft is correctly engaged with the hub and the attachment feedback connectors are coupled properly. Once the attachment is in position, the locking handle can be closed. As the handle is rotated, an axial translation occurs which forces the specifically formed back profile against the inner edge of the bearing. In the locked position, the shaft bearing is held securely between the handle and location pocket thereby preventing any axial movement from occurring. The handle uses an indexed bearing location system to maintain its open / closed positions and features physical limit stops to prevent user misuse.

This particular arrangement of mechanisms results in an exercise module attachment process which is relatively intuitive and safe. The system operation sequence shown in Figure 4.12 details the basic procedure for inserting an exercise module. Once the transfer framework has been position in the correct orientation for the desired exercise, the locking handle should be moved to the open position. Generous tapers (e.g. 45 degree) specified on both the shaft and leading edge of the handle allows the module to be inserted even if the handle is not fully open. The shaft must then be aligned with the hub and inserted until additional movement is prevented by the bearing stop. Once the module is fully inserted, the locking handle can be closed and the exercise can begin. In order to ensure that the shaft is correctly inserted, a switch has been mounted within the assembly which is activated by the handle once the locked position is achieved. The output of this switch is monitored by the software system (see section 5.3.1) which prevents any exercise from being undertaken unless the handle is closed correctly.

A detailed specification of the splined shaft and hub was required to ensure that the system would provide the performance capabilities required. It was assumed, for the purpose of the selection calculations, that the output of the primary resistance system would be transmitted to the module attachment unit without any losses. This represented the maximum theoretical load conditions that the components could experience. The spline details of the bronze hub and steel shaft are shown in Figure 4.13. Using knowledge of the spline geometry and materials in conjunction with common engineering loading factors, the maximum shear stress experienced by these components during a system malfunction could be determined. In this case, the exercise arm would experience a rapid deceleration as the safety systems detailed in section 4.6.3 engage. This emergency stop would result in a high level of shock loading being passed into the module attachment system. As indicated in the Figure 4.13, in the event of a loading condition as previously described, the proposed shaft (maximum shear stress 123 MPa) and hub components (maximum shear stress 32 MPa) would provide sufficient strength to resist the applied forces without deformation.

Figure 4.14 illustrates the two exercise modules which were developed to investigate the attachment concept. A unique exercise bike and arm curl module was manufactured featuring the male elements of the attachment system. The transfer framework could be positioned to align the output axis with the module inputs such that resistance could be applied through the attachment assembly and provide the user with an appropriate training stimulus.



Max force applied to each spline, Fmax :

$$\text{Fmax} = \frac{\text{Toutput}}{r}$$

Where

r = mean radius of spline

$$\text{Fmax} = \frac{373}{0.0125} = 29.84\text{kN}$$

During emergency conditions the shaft will experience heavy shock loading conditions, thus a loading factor must be included where n = 3.

$\therefore$ Ftotal = Fmax × n = 29.84 × 3 = 89.52KN

Max. shear strength required to resist the applied force:

Shear stress :

$$\tau = \frac{\text{load}}{\text{area}} = \frac{\text{Fmax}}{A}$$

Where :

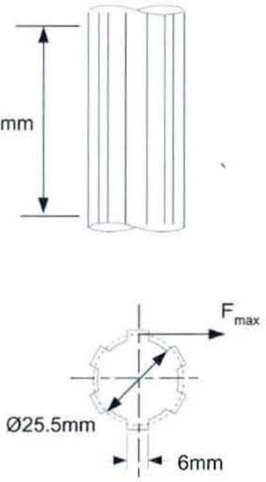
$A = l \times w \times \text{Nsplines}$

and Nsplines = total number of splines

$$A = 0.055 \times 0.00735 \times 6 = 2.43 \times 10^{-3}\text{m}^2$$

$$\therefore \tau = \frac{89520}{2.43 \times 10^{-3}} = 30.84\text{MPa}$$

$\therefore$ Given that the maximum shear stress of the hub bronze material is 32MPa (manufacturers figure), then the proposed hub should be suitable for this application.



Max force applied to each spline, Fmax :

$$\text{Fmax} = \frac{\text{Toutput}}{r}$$

Where

r = mean radius of spline

$$\text{Fmax} = \frac{373}{0.0125} = 29.84\text{kN}$$

During emergency conditions the shaft will experience heavy shock loading conditions, thus a loading factor must be included where n = 3.

$\therefore$ Ftotal = Fmax × n = 29.84 × 3 = 89.52KN

Max. shear strength required to resist the applied force:

Shear stress :

$$\tau = \frac{\text{load}}{\text{area}} = \frac{\text{Fmax}}{A}$$

Where :

$A = l \times w \times \text{Nsplines}$

and Nsplines = total number of splines

$$A = 0.055 \times 0.006 \times 6 = 1.98 \times 10^{-3}\text{m}^2$$

$$\therefore \tau = \frac{89520}{1.98 \times 10^{-3}} = 45.21\text{MPa}$$

$\therefore$ Given that the maximum shear stress of the CK45 steel shaft is 123MPa (manufacturers figure), then the proposed shaft should be suitable for this application.

Figure 4.13: Mechanical analysis of the module attachment system splined transmission components.

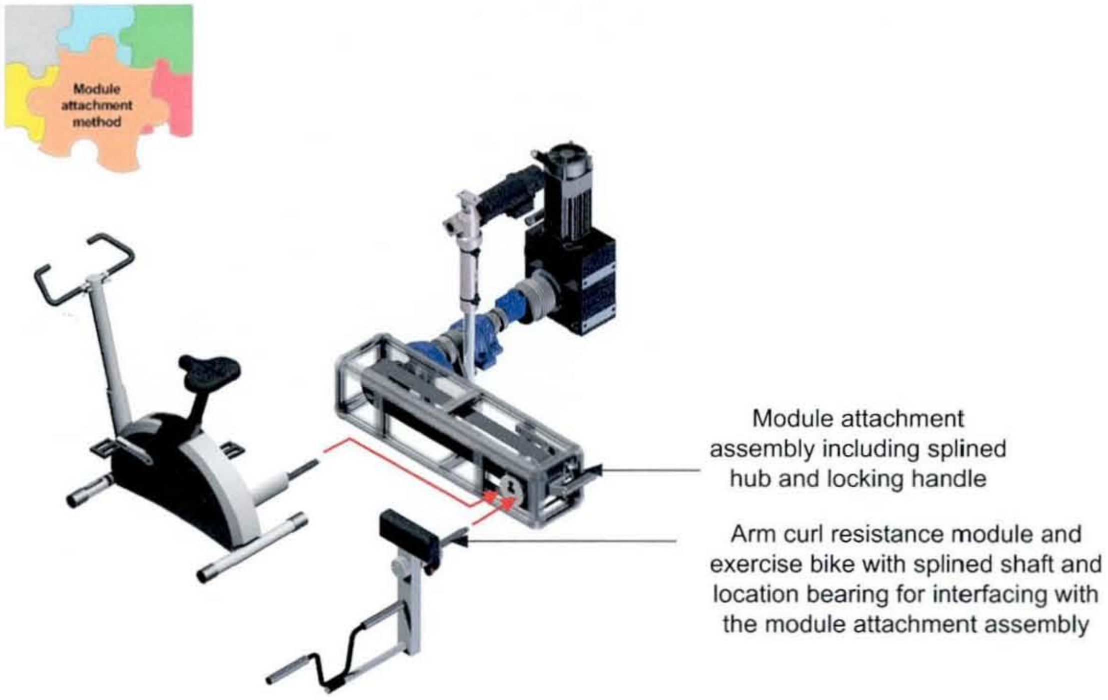


Figure 4.14: Key components and configuration of the module attachment system.

4.6 Integrated safety features

With an active resistance component such as the servo drive system developed for this equipment, user safety was a primary factor in all aspects of the design. In order to ensure that neither the user nor the equipment is adversely effected during normal operation or in emergency situations a detailed failure modes and effects criticality analysis (FMECA) was conducted. This information was used to identify and develop a number of mechanical, electro-mechanical and software systems (e.g. physical limit stops and e-stops) designed to prevent or minimise the consequences of theoretical system instability and malfunction.

Using the requirements outlined in the design specification and the FMECA a number of essential functions were identified that the safety systems must provide (as listed in Figure 4.15). For example, before an exercise can begin, the correct attachment which corresponds to the transfer framework position must be aligned and fully inserted. Both active and passive safety systems were required to prevent injury to the user and damage to the system components in the event that the drive operation was not as expected. Appropriate clearances (e.g. >60 mm) as specified in the relevant governmental standards (British Standard, 2005) were strictly adhered to and potential trapping hazards avoided where possible. Any safety procedures that were established would have to be simple to understand and easy to complete.

A series of concept designs were produced to satisfy these requirements using technology from existing sports equipment, industrial machines and commercial solutions examples of which are shown in Figure 4.15. Given the critical nature of these sub-systems, an evolutionary approach was adopted during the development phase. Initial work focused upon the improvement and adaptation of existing mechanisms (e.g. physical limit stops) rather then on the production of original but completely unproven designs. The individual safety systems are discussed in detail in the following sections.

4.6.1 External emergency stop

The first safety device is an external emergency stop button, similar to that found on many industrial machines. This sizeable push button, positioned to avoid obstruction, is wired directly in series with the main power supply of the servo-drive. In the event of an emergency the switch can be activated and the power supply will be interrupted. Once the connection has been broken, all drive systems will become inactive thereby allowing total freedom of movement of the actuator and associated transmission elements. A reset procedure must be followed in order to reactivate the system. This process should prevent further hazards from occurring and allow the problem to be identified and rectified before allowing the user to continuing exercising.

4.6.2 Module identification system

The inclusion of an adjustable output position mechanism with removable exercise attachments created a number of safety issues. In order to prevent the user from activating the system without correctly inserting the exercise attachment, each module was designed with an electrical connection which interfaced with a socket on the main unit. Once the attachment is partially inserted, such that the weight of the system is supported by the hub assembly, it can be rotated until the connections align and then be full inserted. These connections were designed with a small amount of movement to compensate for misalignment and fit together closely once the attachment reaches its end stop.

This connection will allow physiological information (e.g. heart rate) to be passed from the exercise attachment to the resistance control system but also carries an identification code. Each attachment is assigned a code which can be recognised by the software (see section 5.3.1). Using this identifier, the system can prevent the user from activating the output if an exercise attachment is inserted into the resistance system when the transfer framework is configured for a different exercise. The electrical connection must be made and a valid code detected by the system before any functionality is enabled. This feature operates in series with the handle switch (section 4.5) and ensures that any attachment is inserted correctly.

4.6.3 Mechanical limit stop device

Mechanical limit stop devices are commonly found on the majority of existing isokinetic dynamometers and are also being incorporated into modern plate loaded and selectorised machines. Limit stop devices are designed to prevent the user from exceeding their maximum range of motion during an exercise. Mechanical stops are positioned to represent the upper and lower limits of movement, between which the user can exercise freely. If a problem is experienced during the exercise, the actuator or coinciding guide will strike the appropriate stop and prevent any further movement.

The two main elements of the mechanical limit stop device developed during this research are illustrated in Figure 4.15. Part A is attached directly to the transfer framework and forms the mechanical stops for the system. A simple rocker arm, pivoted about the base plate is allowing to rotate between two fixed end stops. The range of the permissible movement has been calculated to match the activation distance of two micro-switches positioned on either side of the rocker arm.

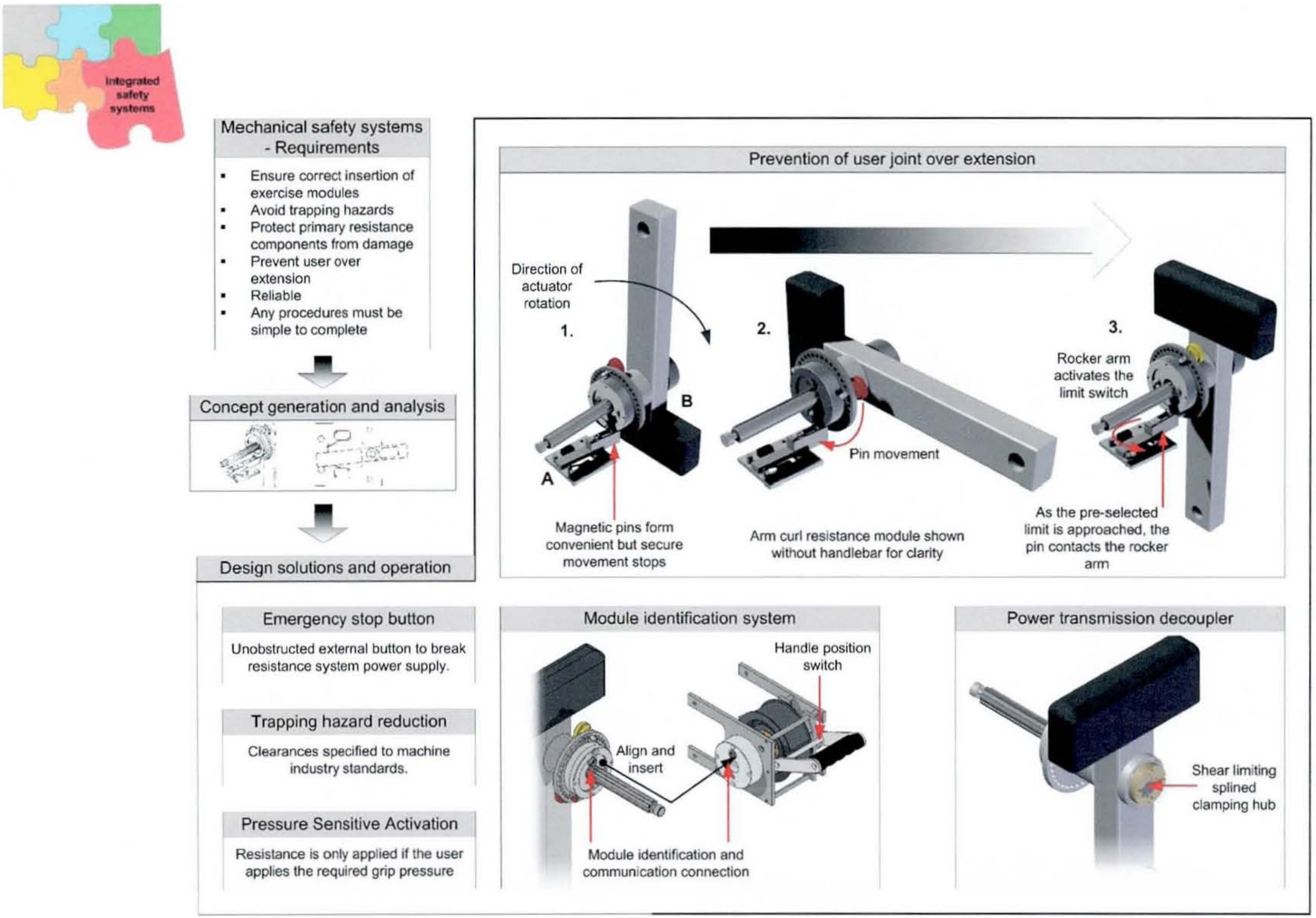


Figure 4.15: Design development and solution features of the integrated safety system.

Part B shows a section of the arm curl attachment and the range of movement selection device. This device is composed of a circular disc, attached directly to the actuator, which includes precision machined holes positioned about its outer circumference at ten degree intervals. These holes are toleranced to provide a close fit with a two location pins. These pins are inserted in the relevant holes to represent the required range of motion and protrude through the rear of the plate. Each pin features a magnetic element which provides an additional holding force against the location plate without restricting insertion / removal.

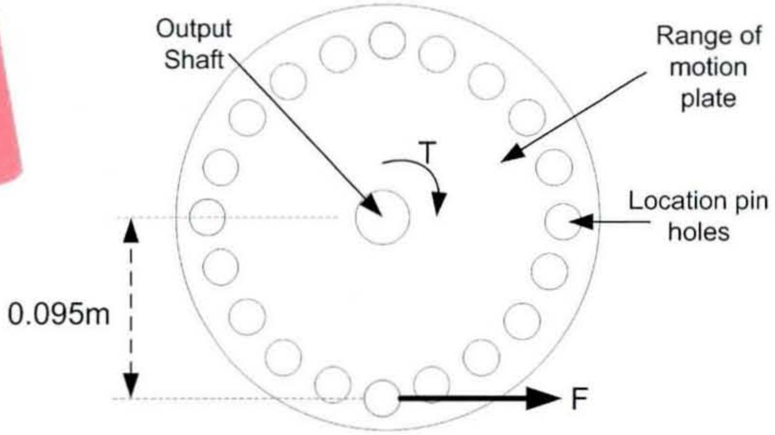
When assembled, the rocker arm is designed to create an interference point with the path of the pin protrusions as they rotate. If control of the system is compromised and the drive system attempts to accelerate the actuator, then the transmission will rotate unobstructed until the location pin strikes the rocker arm as shown in diagram 2 of Figure 4.15. At this point the rocker arm will rotate slightly, activating the micro-switch which instantly terminates all active software programs. If the momentum of the actuator is sufficient or the servo-drive has failed, the limit pin will force the rocker arm into the fixed stop at which point the reaction forces supplied by the device will cause the motor to stall.

The limit stop components have been designed to withstand the maximum operational torque (i.e. 373 Nm) as supplied by the primary resistance system. The calculations shown in Figures 4.16 and 4.17 were used to determine key component dimensions. The maximum force that could be created at the location pin / rocker arm interface was determined initially. Figure 4.16 is a simple illustration of the range of motion location plate. Using the initial geometry proposed in the concept designs, basic material properties and general engineering safety factors, strength critical dimensions of the components could be investigated.

Each limit stop pin is designed to prevent user injury occurring in a situation where a possible unexpected movement of the exercise attachment might be experienced. The pin diameter must therefore be sufficient to withstand an impact with the rocker device at full power as detailed in Figure 4.16. Using the maximum force applied at the point of insertion and assuming that no movement occurs such that the pin is instantaneously loaded, the minimum pin diameter was found to be approximately 7 mm. The final design features a 10 mm outer diameter to improve ease of alignment and insertion of the pin into the location plate.

Assuming that the micro-switches fail to disable the drive, the rocker arm assembly must be capable of withstanding the maximum specified torque. Figure 4.17 is a simple force diagram used to calculate the minimum dimensions of the crucial elements. During a system failure the fixed limit stops are designed to prevent the rocker from rotating once activated by the pin. Therefore it is vital that the diameter of the fixed end stops, indicated by dimension X in Figure 4.17, is calculated correctly. The maximum shear force, F_X, applied to X must balance the impact force from the location pin. Assuming that the rocker arm is free to rotate about the pivot point, this arrangement can be analysed using simple bending theory. The minimum diameter required to resist the shear load of the magnitude described previously was approximately 6 mm. In order to prevent failure of these safety critical components following repeated impacts that may occur during the product lifecycle a final diameter of 10 mm was specified.

Given that the location pins and end stops have sufficient shear strength to withstand continual loading at the maximum operational torque, the rocker pivot and rocker arm were also analysed to prevent failure. The rocker arm pivot outer diameter, (dimension Y in Figure 4.17), can be determined using a similar method to that used for the end stop. Assuming that the end stop is strong enough to support the applied load then this point becomes a virtual pivot location. A minimum diameter of approximately 9 mm was found and resulted in the specification of a practical value of 12 mm which would accommodate for multi load impacts and general design considerations.



Where T = maximum motor torque = 373Nm

$$\tau = F \times d$$

$$\Rightarrow F = \frac{\tau}{d} = \frac{373}{0.095} = 3.926\text{KN}$$

Factor of safety, n = $2.0 \times 1.75 = 3.5$

Using the basic properties of steel the shear strength, τ = 350MPa

$$\therefore \quad \text{Design stress, } \tau_{\text{allow}} = \frac{\text{stress at failure}}{\text{factor of safety}} = \frac{350 \times 10^6}{3.5} = 100\text{MPa}$$

Shear stress:

$$\tau = \frac{\text{load}}{\text{area}} = \frac{F}{A}$$

$$\text{area} = \frac{F}{\tau_{\text{allow}}} = \frac{3926}{100 \times 10^6} = 3.926 \times 10^{-5}\,\text{m}^2$$

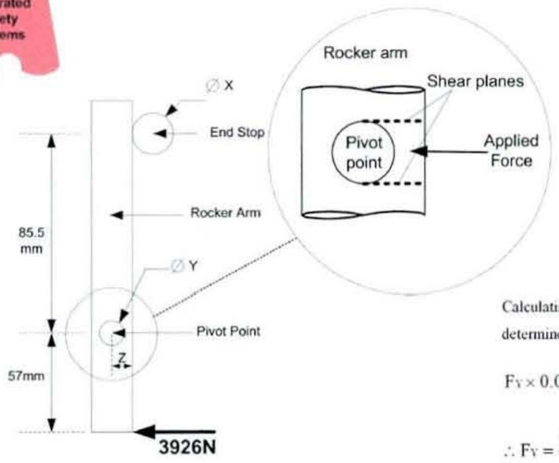
$$\text{area} = \pi r^2$$

$$\therefore \pi r^2 = 3.926 \times 10^{-5}$$

$$r = \sqrt{\frac{3.926 \times 10^{-5}}{\pi}} = 3.535 \times 10^{-3}\,\text{m}$$

$\therefore$ Pin diameter required to resist the shock load of impact with limit stop = 7.1mm. Thus the current 10mm diameter pin is suitable.

Figure 4.16: Mechanical analysis of the physical limit stop pin components.



The maximum shear force, F_X applied to X must balance the impact force from the location pin. Assuming that the rocker arm is free to rotate about the pivot point, this arrangement can be analysed using simple bending theory.

$$F_X \times 0.0855 = 3926 \times 0.057$$

$$\therefore F_X = \frac{3926 \times 0.057}{0.0855} = 2617\text{N}$$

Shear stress:

$$\tau = \frac{\text{load}}{\text{area}} = \frac{F}{A}$$

$$\text{area} = \frac{F_X}{\tau_{\text{allow}}} = \frac{2617}{100 \times 10^6} = 2.617 \times 10^{-5}\text{m}^2$$

$$\text{area} = \pi r^2$$

$$\therefore \pi r^2 = 2.617 \times 10^{-5}$$

$$r = \sqrt{\frac{2.617 \times 10^{-5}}{\pi}} = 2.886 \times 10^{-3}\text{m}$$

$\therefore$ The minimum end stop diameter required to resist the shock load of impact of the rocker arm = 5.8mm.

Calculating the rocker arm pivot outer diameter, Y, can be determined using a similar method to that used for the end stop.

$$F_Y \times 0.0855 = 3926 \times 0.1425$$

$$\therefore F_Y = \frac{3926 \times 0.1425}{0.0855} = 6543\text{N}$$

Shear stress:

$$\tau = \frac{\text{load}}{\text{area}} = \frac{F}{A}$$

$$\text{area} = \frac{F_Y}{\tau_{\text{allow}}} = \frac{6543}{100 \times 10^6} = 6.543 \times 10^{-5}\text{m}^2$$

$$\text{area} = \pi r^2$$

$$\therefore \pi r^2 = 6.543 \times 10^{-5}$$

$$r = \sqrt{\frac{6.543 \times 10^{-5}}{\pi}} = 4.564 \times 10^{-3}\text{m}$$

$\therefore$ The minimum rocker arm pivot diameter required to resist the shock load of impact of the rocker arm = 9.2mm.

The minimum rocker arm cross section required to resist the shear load across the sections between the edge of the arm and the pivot is shown below. Assuming that the force applied across these faces is the same as that applied to the pivot.

$$\text{area} = \frac{F_Z}{\tau_{\text{allow}}} = \frac{6543}{100 \times 10^6} = 6.543 \times 10^{-5}\text{m}^2$$

$$\text{area} = 2(h \times z) \qquad \text{Where } h = 0.03\text{m}$$

$$\therefore 2(h \times z) = 6.543 \times 10^{-5}$$

$$h = \frac{6.543 \times 10^{-5}}{0.03} = 1.091 \times 10^{-3}\text{m}$$

Figure 4.17: Mechanical analysis of the limit stop rocker components.

Finally, it is conceivable that the rocker arm may shear across the sections between the edge of the arm and the pivot as shown in Figure 4.17. Assuming that the force applied across these faces is the same as that applied to the pivot, the minimum cross section of the rocker could be determined as 1.1 mm. The rocker arm was designed to accommodate the pivot elements and a 2 mm thick nylon washer which acts as the bearing surface between the rocker arm and pivot. The additional width required to resist the shear force was added to the pivot dimensions to give an overall size. Therefore the final design featured a rocker width of 22 mm which ensures that the integrity of the system is maintained even during repeated failure conditions.

4.6.4 Power transmission decoupler

In the occurrence of a system malfunction that results in the activation of the limit stops device, it is important to protect the key rotary power transmission components from permanent damage. If the drive system fails to deactivate once the micro-switches have been triggered then it is possible that the motor will continue to drive against the end stops, at maximum torque, until the system is shut down manually. If the motor is allowed to continue operating in this stalled condition for a sufficient period of time, the resultant heat generation could compromise the performance of the internal components. Reparation of any damages sustained to the motor is both costly and time consuming, therefore it is common practice in industry to introduce a torque limiting device which decouples the primary drive from the output once a predefined torque level is attained.

There are a number of means for providing this mechanical safety which vary in complexity, operation, maintenance and cost. Clutch based systems are common in high volume production equipment where any machine downtime should be avoided. These systems, based upon principles of frictional engagement, operate without slippage until the specified torque level is exceeded. Once this limiting value has been reached, the system will decouple and allow the input drive to rotate freely without influencing the output. If the torque level drops below the specified level, the system will re-engage. This feature makes these torque limitation devices unsuitable for a resistance exercise system since if the user has inadvertently become trapped by the actuator in the event of a major failure, it is critical that the applied load is terminated immediately. If a limiting slip system is used, the load will continue to be applied as long as the output torque does not exceed the unit tolerances.

A simple and cost effective alternative to these integration solutions was the inclusion of a torque limiting spline. This arrangement is designed to introduce a controlled weak point in the transmission system to ensure that failure will occur in the event that the driven load becomes locked at maximum torque. The clamping rings which connect the splined shaft to each exercise attachment have been modified to reduce the strength of the component by reducing the effective contact area of splines. The exact length of the splines (i.e. 4.4 mm) has been determined by the shear stress created by the system at maximum load.

A sudden rise in the transmission torque will cause the splines to shear due to the shock load, thereby breaking the link between the shaft connections and permanently disconnecting the primary drive source. The rings are positioned in a convenient location on the exercise attachment to minimise replacement times in the event of a failure (see Figure 4.15). By incorporating the failure mechanism into the exercise attachments in this manner, the level of maintenance required for the main resistance unit can be minimised assuming that the initial failure can be rectified simply. The resistance system can be re-commissioned and returned to normal operation whilst the damaged exercise attachment is repaired.

4.6.5 Pressure sensitive activation switches

The identification, selection and commissioning procedures for a range of different pressure sensors were investigated during the design development process. A monitoring system was devised which consists of pressure sensitive materials positioned at strategic points on each exercise attachment to measure the applied force over the sensor area (e.g. the handlebar grip on the arm curl attachment). The output from these sensors is used as an activation signal for the main resistance system.

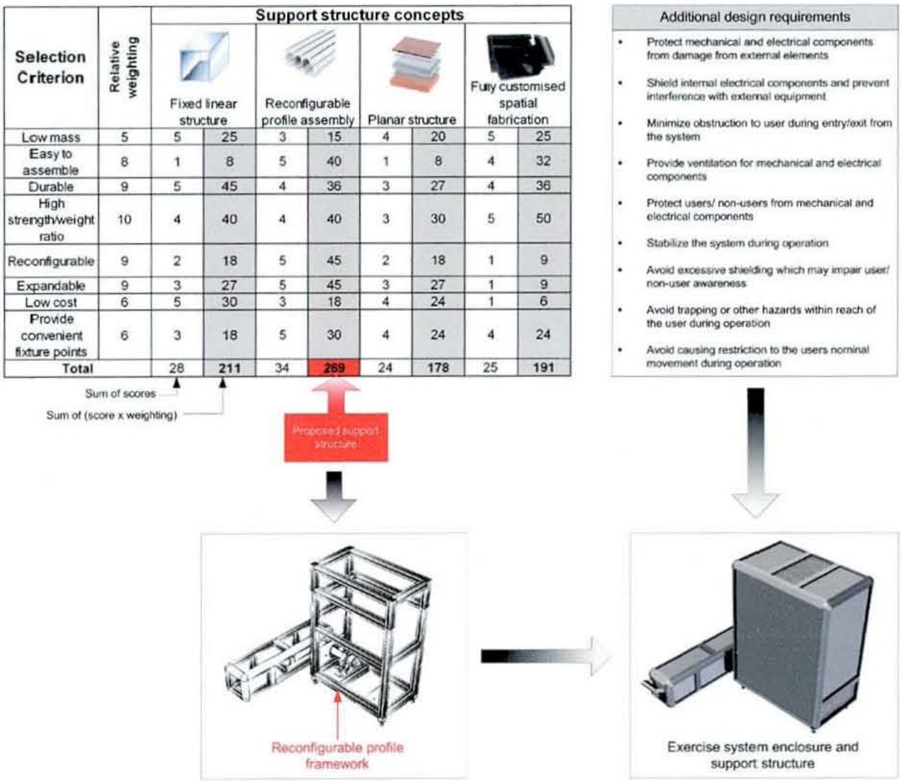
Test data was used to determine a minimum threshold pressure which would act as the switching trigger. Once the user begins an exercise, they must apply an appropriate force to the handlebar grip at all times. The output data is monitored in real time and compared with the minimum reference safety levels. If the pressure applied drops below the minimum level, the active software program will implement a controlled stop procedure (see section 5.3.1). The system will wait in this temporary interrupt condition until the user returns to the correct position and continues with the exercise or chooses to exit the current routine.

4.7 Support structure design

Once the core mechanisms of the system had been defined, the supporting structure could be developed to suit the internal component dimensions. The support structure forms the physical link between the individual drive and control elements and ensures that the spatial relationships are maintained. A selection of construction methods were identified, as shown in Figure 4.18, which could form the basis of the resistance machine support structure. The suitability of each of these construction approaches was analysed using a modified evaluation matrix as used throughout the system development process. A list of general selection criteria (e.g. high strength / weight ratio, reconfigurable and durable) were extracted from the design specification against which each solution would be assessed. These criteria were assigned a weighting as per previous examples to indicate the relative importance of each factor. Each structure was awarded a score based upon its ability to satisfy each design criteria and the sum of the scores was used as a quantitative measure of the overall suitability of each approach.

As indicated in Figure 4.18, the support structure concept awarded with the highest overall evaluation score was the reconfigurable profile assembly. A large number of commercial systems are available which utilise customisable extruded aluminium sections with standard fixtures to create varied frameworks and structures. This approach drastically reduces assembly times and introduces a level of flexibility in the structure that can not be achieved readily with permanently fixed methods.

Following the identification of a suitable construction system, the detailed configuration of these elements to produce a complete support structure could be explored.



Selection Criterion	Relative weighting	Support structure concepts							
		Fixed linear structure		Reconfigurable profile assembly		Planar structure		Fully customised spatial fabrication	
Low mass	5	5	25	3	15	4	20	5	25
Easy to assemble	8	1	8	5	40	1	8	4	32
Durable	9	5	45	4	36	3	27	4	36
High strength/weight ratio	10	4	40	4	40	3	30	5	50
Reconfigurable	9	2	18	5	45	2	18	1	9
Expandable	9	3	27	5	45	3	27	1	9
Low cost	6	5	30	3	18	4	24	1	6
Provide convenient fixture points	6	3	18	5	30	4	24	4	24
Total		28	211	34	269	24	178	25	191

Additional design requirements

- Protect mechanical and electrical components from damage from external elements
- Shield internal electrical components and prevent interference with external equipment
- Minimize obstruction to user during entry/exit from the system
- Provide ventilation for mechanical and electrical components
- Protect users/ non-users from mechanical and electrical components
- Stabilize the system during operation
- Avoid excessive shielding which may impair user/ non-user awareness
- Avoid trapping or other hazards within reach of the user during operation
- Avoid causing restriction to the users nominal movement during operation

Figure 4.18: Quantitative analysis of support structure elements against key selection criteria.

The mechanical architecture of the resistance exercise system has a number of important design requirements as listed in Figure 4.18. Careful consideration was given to the most appropriate design solutions for satisfying each of these functions. Aesthetic appearance was not considered as a primary issue during the development process as the main focus of this research is the investigation of novel mechanical, electrical and software systems for use in academic and clinical studies. The development of the aesthetics of the prototype toward a more suitable commercial product has been identified of a requirement for future research and development (see Chapter 8).

4.7.1 Framework design and internal component layout

By supporting the gearbox vertically and sequentially coupling the rotary transmission elements in line with the reference output axis as outlined in section 4.2, the design of the framework could be focused upon the connection and protection of the components. A simple rectangular frame was proposed that would encase the drive system and optimise the assembly strength of the proposed profile sections. A simple sketch of the basic framework that can be used to illustrate the key features of the design is given in Figure 4.18.

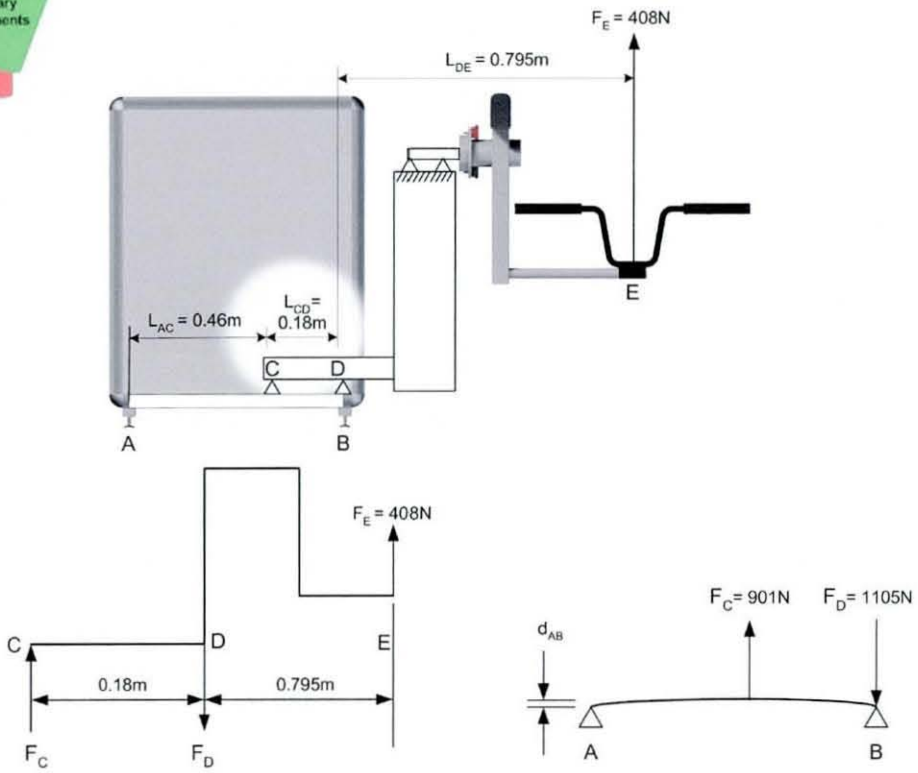
The dimensions of the framework were designed to minimise the overall envelope whilst ensuring that the minimum component clearances were maintained. In order to maximise the stability of the support structure, internal components were positioned as close to the base as practical. The main structural members consist of prefabricated 40mm square section aluminium tubing which is drawn in specific profiles to form part of an integrated construction system. This approach allows the structural members to be moved and reconfigured with minimal effort whilst maintaining structural integrity.

Different structural components were positioned within the overall framework to provide specific attachment and bracing functions. The transfer framework is connected to a hollow cylinder which is supported by a pair of bearing blocks attached to the main structure. This cylinder is restrained axially but can rotate relative to the base unit. A section of this pivot has been designed to accept a cam mechanism as described in section 4.3. The static section of the linear actuator is attached to the support structure such that any extension/retraction will result in a rotational movement of the cam and cylinder about the central axis. This motion is transmitted directly to the transfer framework and thus allows the system to be reconfigured for different exercises. The additional weight of the transfer arm and internal drive components positioned externally on the side of the main resistance unit is counterbalanced by the mass of the servo motor and gearbox.

The internal skeletal structures of the main unit and transfer framework are covered by a protective enclosure which is constructed from similar profiles and panelling as shown in the CAD visualisation in Figure 4.18. The high impact panelling prevents external access to the mechanical components and should contain any debris that may be produced in the event of a major failure. Ventilation ducts have been included at the base and top of the main casing. Given the volume of air within the framework and predicted low level heat generation during normal use, it was decided that the process of natural convection would be sufficient to maintain normal operating temperatures (i.e. -20-40 °C). Additional electrical shielding of the internal components was not required as the individual control and monitoring units were supplied with integrated shields and connected to minimise interference.

Trapping hazards which are common in existing resistance equipment have been minimised by ensuring that suitable clearances were specified between moving parts. Excessive shielding of the transfer framework has been avoided to prevent the creation of additional hazards and provide an unrestricted line of sight during reconfiguration.

The precise dimensions of the connection plates and the configuration of the framework members have been designed to withstand the maximum specified system torque as shown in Figure 4.19. It was assumed that the user load is applied through the handlebars of the arm curl attachment at a single point. Therefore, the maximum force applied at the bearing supports is a result of the bending moment created by the user when conducting an exercise at full resistance. Using a simplified bending moment diagram, the forces about the main support points can be resolved. This analysis confirmed that the framework connections would provide sufficient strength to hold the load. Deflection in the extruded framework elements, d_{AB}, was found to be negligible (maximum deflection = 0.62 mm) and therefore the proposed support structure would be suitable for the nominal operation conditions. By utilising a flexible profile system such as this, any increase in drive capabilities or additional design features can be implemented or compensated for easily and efficiently.



Reaction forces in bearings at points C and D

Taking moments about point D

$408 \times 0.795 = F_C \times 0.18$

$$F_C = \frac{408 \times 0.795}{0.18}$$

$F_C = 1802N$

Resolving vertical forces

$F_C + F_E = F_D$

$F_D = 1802 + 408$

$F_D = 2210N$

If force F_C is applied across two parallel beams, the resultant force on each AB member is 901N. Using the manufacturers data, failure will occur at the beam connection points at 3500N (for the preferred profile section, joint method and support configuration). Thus the framework should provide sufficient strength for normal operating conditions.

Deflection in beam AB at maximum load

$$d_{AB} = \frac{F \times L^3}{E \times I \times 48 \times 10^4}$$

Where d_{AB} = deflection
F = applied load
L = unsupported length
I = Moment of inertia
E = Young's modulus

$$d_{AB} = \frac{901 \times 640^3}{70000 \times 11.3 \times 48 \times 10^4}$$

$d_{AB} = 0.62mm$

Figure 4.19: Static load analysis of the support structure during maximum operating conditions.

4.7 System embodiment and operation

The rotary power transmission system elements and servo components are illustrated in Figure 4.20. The parallel alignment between the gearbox output and the transfer framework reference axis can clearly be seen. During the rotary power transmission selection process, a number of additional motion control components were identified that must accompany the basic mechanical elements in order to create an integrated servo drive system. This hardware provides the necessary control and input/output capabilities which allow the required levels of performance, safety and feedback to be achieved. The additional servo drive elements consisted of two major systems, the servo drive (Lenze 9324) and the motion controller (Trio Motion MC206).

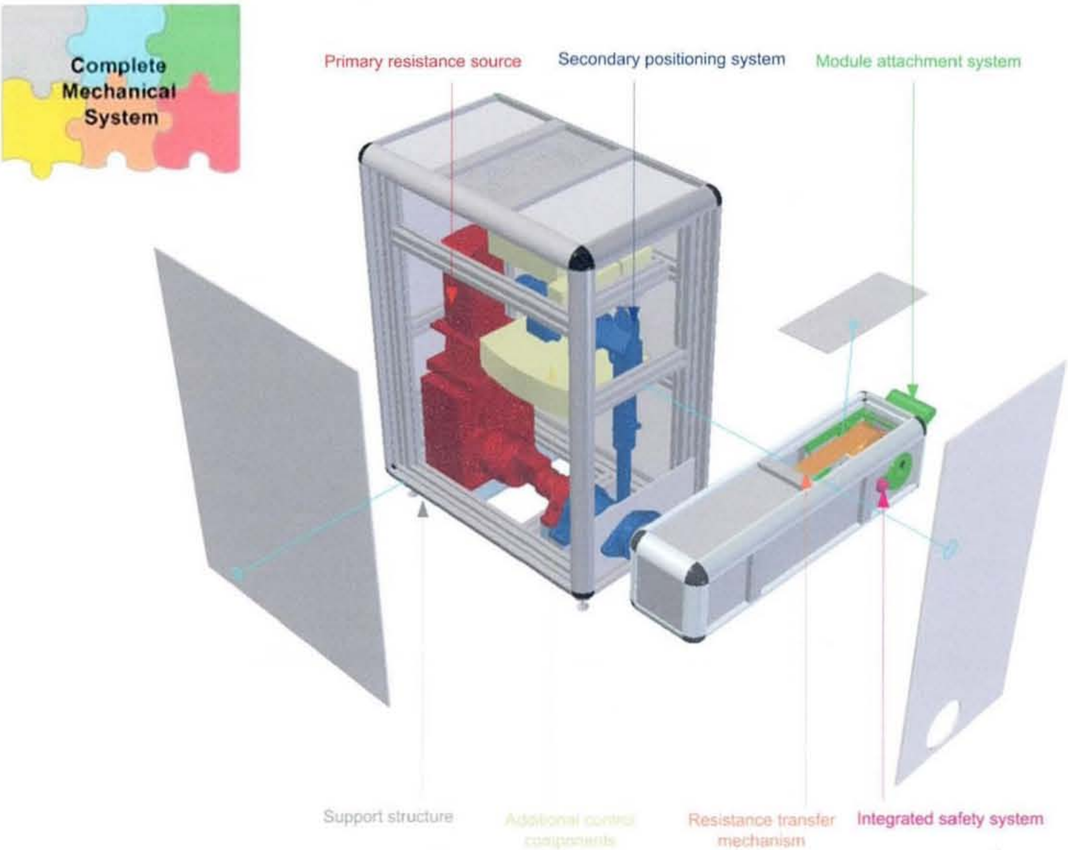


Figure 4.20: Complete exercise system including all key mechanical elements.

The servo drive converts the output signals from the motion controller into an appropriate format that can be used to drive the motor. Information regarding the required position, velocity and torque are fed into the controller which then determines current and voltage supplies for the motor. In this arrangement the servo drive also receives resolver feedback although this information is only utilised by the motion controller. The motion controller conducts a comparison between the measured and desired parameter values (i.e. speed and/or requested torque profiles) and outputs the required adjustments to the servo drive. The servo drive has been selected to suit the characteristics of the preferred motor and available power supply. The unit is supplied in a force ventilated, electrically shielded casing with specific mounting points for direct attachment to the framework of the system.

The motion controller receives inputs from the main human machine interface (see Chapter 6) and generates outputs that are used by the servo drive as control signals for the motor. In a closed loop system such as this, information regarding torque, position, acceleration, deceleration and velocity are specified by the required training profile and system response requirements and converted into appropriate outputs by the motion controller. The motion controller selected for this application was designed to interface effectively with the preferred servo drive to enable a wide range of operational and safety inputs to be processed simultaneously and relevant actions implemented swiftly. This controller was selected for its versatile software and ease of integration with the proposed servo hardware.

A CAD sequence illustrating the process of reconfiguring the system for different exercises is represented in Figure 4.21. The system is initially configured with the transfer arm in a vertical position suitable for an arm curl exercise. If the user wishes to train a different muscle group or change to an aerobic exercise device, the active session must be completed or aborted. Once the machine has been set to an idle state, the attachment can be removed as discussed in section 4.5. The desired configuration can then be selected and the system will automatically rotate to the corresponding position. Assuming that the move is completed successfully, the new attachment can be coupled to the resistance unit and secured. If the various safety interlocks are closed correctly, the user will be permitted access to the setup process for the module selected, the exercise bicycle for instance, as shown in Figure 4.21.

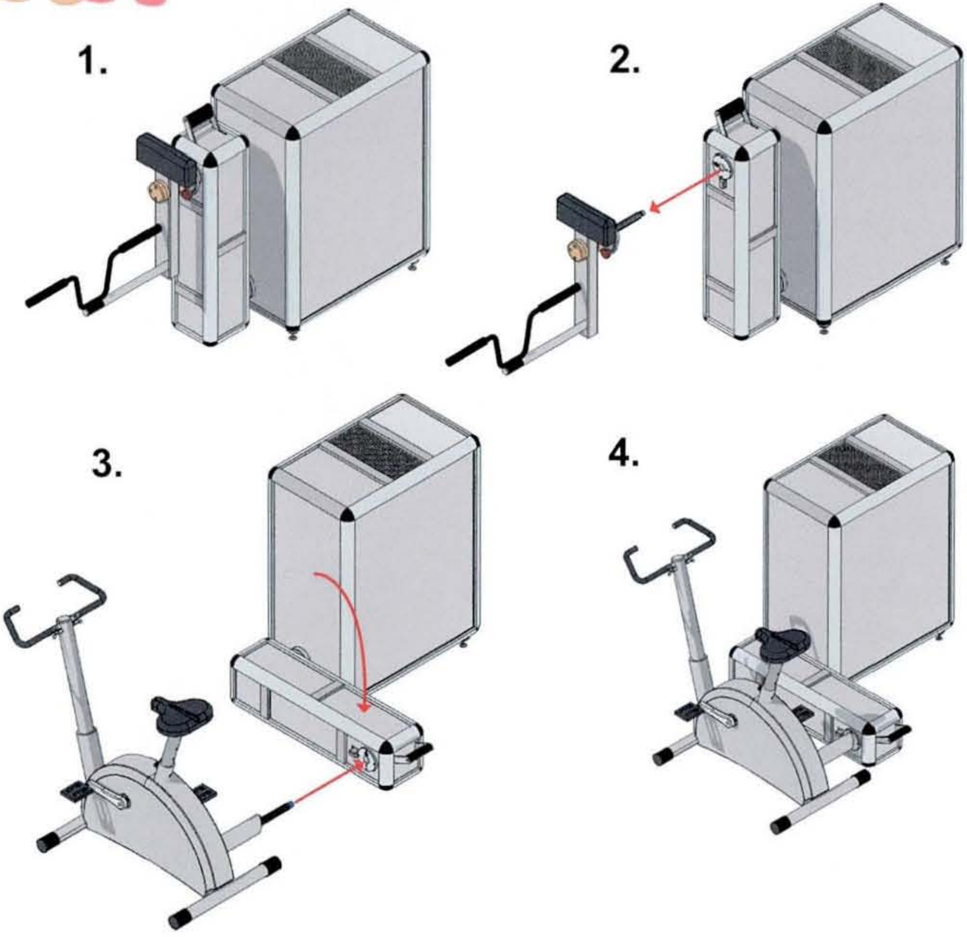


Figure 4.21: CAD sequence illustrating the process of system reconfiguration from resistance to aerobic exercise.

4.8 Further developments

During the development of the mechanical and electro-mechanical systems, a small number of innovative design concepts were proposed but not fully developed during production of the prototype system. These systems would provide additional but non-essential functions as defined in the design specification and were therefore omitted during this initial development phase.

(i). Limit stop pin location feedback

In addition to the mechanical components of the limit stop device, an electro-mechanical system was conceived to monitor the location of the pins. This system was designed to ensure that the pins are fully inserted into the location holes. If the overlap between the pin and rocker is insufficient, the attachment may rotate beyond the users maximum range of motion and cause injury. The proposed solution would also monitor the position of the pins around the location plate. It was envisioned that automatic checks would be conducted in the software to confirm that the pins were inserted in the relevant positions that correspond to the users range of motion. If the pin positions are determined to be incorrect, the software will prompt the user to rectify the error and wait idle until the correct configuration is achieved

Each of the location pins features a small magnetic element which helps to secure the component in position. This magnet will be used to activate Hall effect switches placed at each hole in the plate. A customised flexible PCB circuit would be developed to mount these switches and connect the outputs to a basic PIC microcontroller unit. Power to the system could be supplied through the electrical connection incorporated into each exercise attachment. This link could be modified to include controller area network (CAN) or any other suitable communication protocol for transmitting pin location information to the control system.

(ii). Physiological feedback

Aerobic exercise equipment provides some form of fundamental physiological feedback (e.g. heart rate, body temperature). This information is generally used as a passive indicator for the user to monitor their status and provides rudimentary active exercise control. During the development of the prototype training system, a physiological feedback scheme was devised which was not found on existing resistance training equipment. Each exercise attachment could be fitted with basic physiological sensors to monitor the required parameters. The user may choose to monitor this information through the user interface as discussed previously. However, in the proposed system this data would also be monitored by the software.

Real time analysis of the condition of the user could be conducted to prevent over exertion and possible injury. Individual user performance characteristics would be required which could be mapped onto a set of general safety algorithms to provide a customised exercise monitoring system.

(iii). Additional pressure sensors

The technology utilised in the exercise attachment pressure activation switches could be expanded to provide additional safety features. By embedding pressure sensors in the training equipment at strategic points, information regarding user posture and loading could be recorded. Additional software could be developed to analyse this data and ensure that the correct position is maintained during each exercise and avoid excessive load being applied to any specific anatomical point.

4.10 Summary

The structured approach adopted during the mechanical resistance system development process resulted in the creation of a tightly defined, well integrated solution which was successfully used to produce of a fully functioning prototype unit as shown in Figure 4.22. This arrangement provided the necessary capabilities for accurate control of torque, position, speed and acceleration in an effective and efficient manner. Operation of the servo system is monitored and controlled via a human machine interface and processing unit as discussed in Chapter 6 which communicates with the motion controller via a USB link.

A complete rotary power transmission was developed to provide the necessary functional capabilities. The output of this drive system is transferred via an adjustable framework to allow the unit to be reconfigured for a range of different exercises. Each exercise requires a unique attachment which is connected to the resistance device via a quick release system.

Figure 4.22: Photo of the complete exercise system in a resistance exercise configuration.

A basic framework was designed to support and align the resistance system elements. The structural components of this framework utilise a reconfigurable profile system which allows changes to be made to the design of the equipment during testing and further research. A simple but effective cover was designed to protect the internal components and prevent user injury. A range of safety systems were developed from a detailed failure modes and criticality analysis in order to protect the user in the event of a system failure. These mechanical and electro-mechanical systems ensure that system conforms to all of the relevant safety standards and matches or exceeds the equivalent protection currently offered on existing resistance training equipment.

Chapter 5

Low level software development

5.0 Introduction

The electromechanical solution described in Chapter 4.0 has been developed using common industrial control systems which must be integrated and operated by appropriate control software. The software discussed in this chapter utilises software code that has been established using research knowledge. The resistance exercise system utilises well-known programmable motion control concepts and standardised hardware in a unique application. A detailed description of the system software functionality in relation to the different modes of exercise is covered in this chapter. Critical safety features that have been specified are also defined together with data collection and storage procedures.

A schematic of the hardware components in the current embodiment is shown in Figure 5.1. The diagram identifies the main hardware components and also the information that is passed between these modules. Low level program code has been developed to record, analyse, manipulate and send this information between the various hardware systems in order to achieve the desired functionality. Although this is a specialist platform, system flexibility is high as the control signals can be configured for any commercial motor and servo combination.

5.1 Programmable hardware systems

The control system developed for the resistance exercise equipment consists of a number of programmable hardware elements which provide the necessary computational capabilities required to control the operation of the primary resistance source and associated transmission components. There are three primary systems in the resistance exercise device which have been used as interrelated programming platforms: the processor, the motion controller and the servo drive. These systems could be configured in a number of alternate ways to provide the required motion control. The arrangement used in the development of the resistance exercise is discussed in the following sections together with details of the core function of each element.

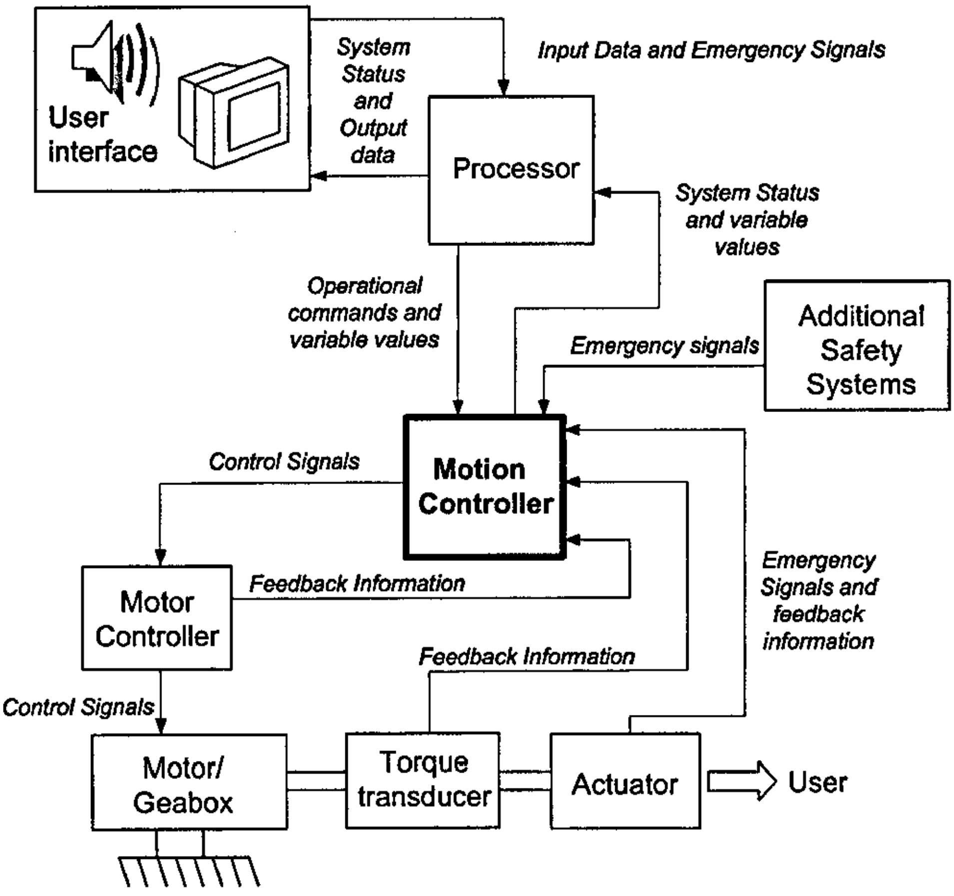


Figure 5.1: Schematic of the drive system and associated control signals.

5.1.1 Processor

The system detailed in Figure 5.1 uses a standard desktop PC unit to act as the "Processor". For the purposes of development, this arrangement offered a suitable environment for the various proprietary software tools that were required to develop the system code and also provided the range of input / output connections for communications with the various hardware modules. This Processor unit could be setup as the primary system for programming and controlling the servo drive. In this configuration, code processing and data recording would be restricted by the performance characteristics of the PC and its operating system. For an application requiring high speed, closed loop control such as the exercise system, this could severely limit dynamic response. Therefore, real time control programs were developed to operate on the dedicated motion controller which would provide the necessary cycle rates (e.g. minimum 250 μs) and pseudo deterministic operational capability.

Although the PC was not used for direct motion control, it was utilised as a platform for developing the motion controller code. The software code was generated and tested using the supplied PC simulation environments. Finalised versions of the programs could then be downloaded via USB 2 connections and stored in the motion controller. Ideally the system processor could be reduced to a basic industrial PC, utilising a single card based solution (e.g. industrialised PC104) in future instantiations. Given the correct specification, a single card unit will provide the necessary functionality and connectivity to operate the system in a small but highly customised package.

The development software (TrioMotion Motion Perfect 2 V 2.3.1.10) supplied with the motion controller (i.e TrioMotion MC206) allows the code to be developed and tested independently of the unit. New or revised programs can be transmitted via the Internet or uploaded from potable storage devices directly into the individual units in an appropriate form. This code can be saved to the Processor and uploaded to the motion controller without the need to activate any processor based software or specialist hardware.

The PC also forms the basis of the human-machine interface (HMI). This interface forms a link between high level, user-orientated functions and the low-level motion control requirements. This aspect of the Processor's functionality and the design and operation of the HMI is discussed in detail in Chapter 6.

5.1.2 Motion controller

The motion controller generates outputs based upon the inputs received from the processor and the internal program structures that are stored in the unit's memory. The resultant output signals are used by the motor controller as control signals for the motor via the servo drive unit. In a closed loop system, information regarding torque, position, acceleration, deceleration and velocity are specified by the user and converted into appropriate outputs by the motion controller. The motion controller also collects real time data regarding these parameters which can be stored and transmitted back to the Processor. A universal serial bus (USB) connection was selected to provide high-speed communications (50 mbs) between the processor and the motion controller. The motion controller has a recommended minimum process cycle time of 1ms, although this can be further reduced to 250 μs if required. These cycle times are dependent upon the number of processes that are required to operate in parallel.

Each cycle period is divided in such a way that two nominated high priority programs are processed every cycle count (i.e. every 1 ms) with the remaining time distributed between non-critical operations. In the resistance exercise system there may be a maximum of four programs running simultaneously at any point in time. Two priority programs have been developed, the first establishes communications with the servo drive and the processor whilst the second monitors safety systems and controls the activation of non-critical programs. This configuration ensures that during periods of maximum operation the controller will cycle through all 4 programs every 2.5 ms.

The maximum exercise speed requirements are likely to be achieved when the system is configured for an aerobic exercise such as the exercise cycle (see Chapter 2, section 2.2.1). Using the performance figures determined in Chapter 2, the system will need to operate at a maximum of approximately 280 rpm in order to accommodate the training requirements of competitive cyclists. Therefore, in the current configuration the system will complete a full process cycle for every 4.67 degrees travelled by the pedal arm. If the maximum speed of the resistance exercises is limited to 500 degrees per second, the resolution of the data storage program in this scenario will equate to a data point every degree. This resolution should provide good quality data for analysis during high speed testing while maximising the systems response to emergency signals which is essential for the prevention of damage to the equipment and injury to the user.

5.1.3 Servo drive

The servo drive (Lenze 9324 servo drive) selected for this application has been configured to operate specifically with the preferred servo-motor. Communications between the servo drive and motion controller are conducted using a number of different protocols. Simple analog links are used to input speed and torque set point references. A digital link has been created to control activation of the unit using the "watchdog" feature of the motion controller. This "watchdog" is a relay contact used to enable the drive before executing operational programs. The "actual" torque data, recorded by the transducer, is transferred via CAN (update period 5 ms) and the motor encoder signal is passed via a proprietary link (update period 1.6 μs).

The drive has been configured to operate with the specified hardware in a nominal speed control mode although the operation of the unit can be reconfigured by the motion controller using the supplied CAN link. In this nominal state, the unit is pre-programmed to utilise a set percentage of the available torque to maintain the required velocity as defined by the motion controller. If an error is detected between the actual speed and set speed, the servo will automatically attempt to rectify this difference by adjusting the torque accordingly.

The motion controller has been programmed to send a digital signal via the CAN link which when received by the servo drive causes the unit to switch from speed control to torque control. In this mode, the drive will attempt to provide an output torque of the required magnitude regardless of the applied load. A velocity reference can be specified to prevent the system from becoming unstable in the event that the load is suddenly removed.

5.2 Low level software structure

The process of the "low level" software design was initiated by establishing a clear understanding of the information requirements of a modern exercise system. A general requirements map was generated using knowledge from the PDS (see appendix A) and CIMOSA diagrams. This "map" has been translated into a detailed process plan, which outlines the precise information inputs, transfers, processing requirements and outputs for the low level software system.

This process model was constructed using existing knowledge developed within the research group and has been transferred into a series of software modules with specific functionality and data flows. The resultant software structure as shown in Figure 5.2 combines industrial servo control principles with specific exercise procedures and data requirements. The low level software system operates in parallel with the HMI (see Chapter 6) and servo drive programs. Activation signals and data are transmitted between the control elements to produce an integrated system.

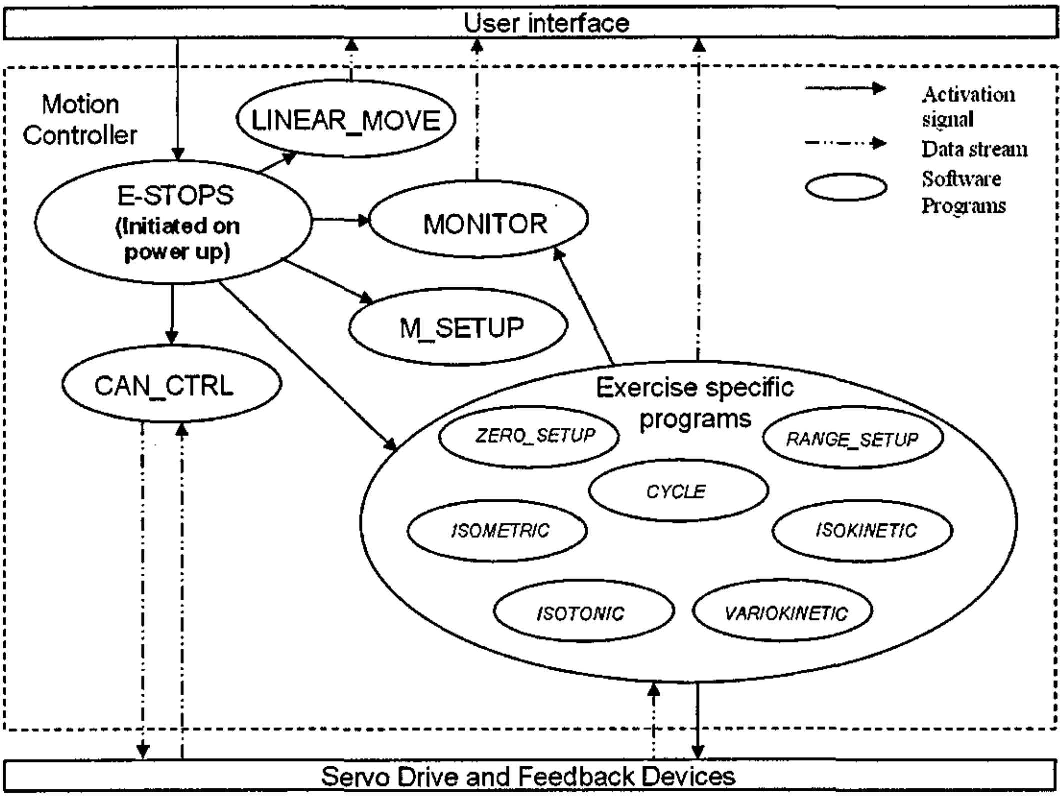


Figure 5.2: Low level system software structure.

For efficient operation, the motion control programs are designed to form a simple master / slave configuration. In this arrangement, the two high level priority programs call additional functionality only when it is required, thereby reducing process cycle times and maximising system response. In the current system, E_STOPS has been selected as the master program. Upon activation, E_STOPS automatically initiates three additional programs; M_SETUP, CAN_CTRL and MONITOR. The main function of E_STOPS is to monitor the e-stop and emergency input signals and take appropriate action. The motion controller is configured to launch this program automatically once power is supplied to unit and will continue to run until a disruption in the supply occurs or the system is turn off.

M_SETUP is a variable declaration program which features a standard set of default parameter values that form the nominal velocity, acceleration and torque levels used by the servo drive. This program also defines a set of variables which represent the specific hardware configuration (i.e. operational units, gain parameters, motor details). These variables are essential for correct system control as the different functional components use various combinations of units, ratios and percentages which must be carefully defined.

A CAN communications link has been implmented between the motion controller and servo drive in order to monitor system state, transfer non-standard data to and from each unit and to perform function alterations to the servo drive software configuration. The program CAN_CTRL is a code series which establishes communications between both the servo drive and motion controllers respectively and defines the format of the information that is transferred. Having established the communication protocol the program operates continuously, reading and writing messages between the controllers.

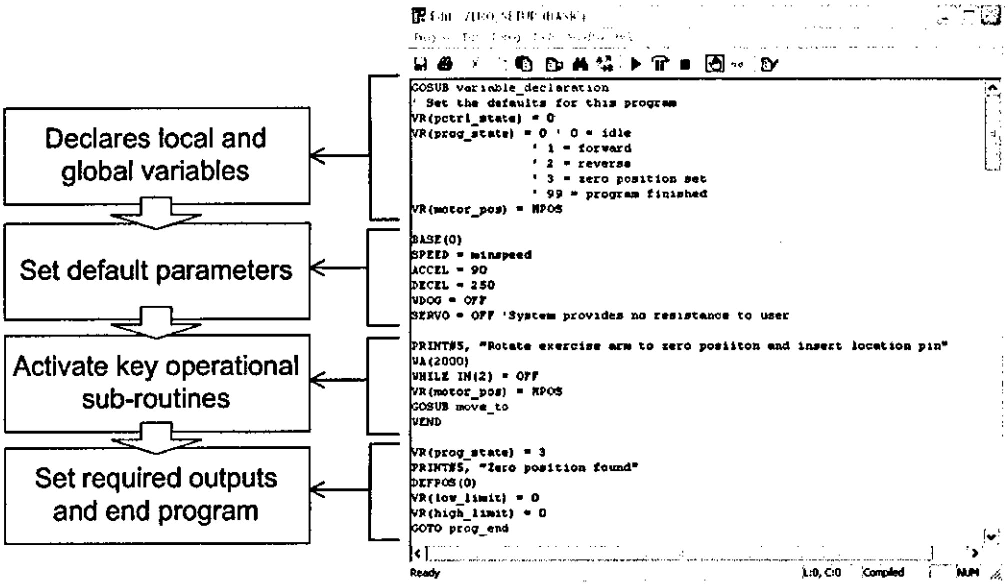
MONITOR is a basic program used to transmit operational information to the user interface. Information such as actuator position, velocity, acceleration and deceleration is constantly available to the user interface, which monitors and updates the appropriate variable when necessary. MONITOR is initially activated by the E_STOPS program but is held in a ready state until an additional signal is received from an exercise program initiated by the HMI. This second signal, which is sent at the beginning of an exercise, initiates the high speed recording function within MONITOR. Data will continue to be collected and temporarily stored until a stop signal is received to signify that the exercise is complete. Upon completion the information is transmitted to the HMI for post-processing, presentation and long term storage whilst the MONITOR program reverts to its dormant ready state.

Once the underlying programs have been initiated, the E_STOPS program waits for the user interface to input a run program variable, the value of which corresponds to a specific integer assigned to a particular exercise program. E_STOPS activates the slave program and monitors its state. Once the slave program has executed, E_STOPS awaits the next "run program" variable input from the processor. Each exercise program transmits unique motion parameters to the servo drive and monitors specific feedback signals. Information regarding the operational state of the program is acquired by the HMI and translated into an appropriate format for the user. The precise operation of these exercise specific programs and their interaction with the E_STOPS program is detailed in section 5.3.

The LINEAR_MOVE program, shown in Figure 5.2, is also activated by the E_STOPS program but is not related to a specific exercise. If the user chooses to exercise a different muscle group or conduct an aerobic exercise, the transfer arm (see chapter 4, section 4.3) must be reconfigured to provide an output at the position requested. The linear actuator is powered by a separate servo drive but is controlled, in parallel with the main resistance system, by the central motion controller. The LINEAR_MOVE program includes the configuration and operation details for the actuator.

If the user selects a different exercise programme through the HMI, E_STOPS will activate the new software. The default actuator parameters are defined initially before the program runs a series of checks to ensure that the actuator has been correctly removed. Once the system is determined to be in a safe state, the user will be prompted to confirm the next exercise and the transfer arm will automatically be driven to the relevant location. Once a move is initiated, the program drives the actuator at a safe speed to the required position. A manual override facility has been provided to allow the user to adjust the precise location of the output. The user may activate the emergency stop at any time during the movement causing the system to stop immediately. The program will wait idle until the user re-initiates the move or selects a different position. Upon completion of the move, the program will send confirmation to the HMI that the correct position has been achieved and will automatically close.

The principal programs which form the basic structure of the low level software system and the programs discussed in the section 5.3 have all been created using the PC based developmental software. The programs are created using a proprietary textual language which defines motion parameters, input / output commands, arithmetic functions and general operational procedures. Figure 5.3 is an example of the code written for the resistance exercise system.



```
GOSUB variable_declaration
' Set the defaults for this program
VR(pctrl_state) = 0
VR(prog_state) = 0 ' 0 = idle
                   ' 1 = forward
                   ' 2 = reverse
                   ' 3 = zero position set
                   ' 99 = program finished
VR(motor_pos) = MPOS

BASE(0)
SPEED = minspeed
ACCEL = 90
DECEL = 250
WDOG = OFF
SERVO = OFF 'System provides no resistance to user

PRINT#5, "Rotate exercise arm to zero posiiton and insert location pin"
WA(2000)
WHILE IN(2) = OFF
VR(motor_pos) = MPOS
GOSUB move_to
WEND

VR(prog_state) = 3
PRINT#5, "Zero position found"
DEFPOS(0)
VR(low_limit) = 0
VR(high_limit) = 0
GOTO prog_end
```

Figure 5.3: Annotated example of the proprietary code developed for the motion controller.

5.3 Exercise specific software operation

The operation of the various exercise programs developed for the resistance training system are discussed in detail in this section with reference to the basic diagrams created to provide a visual representation of the system requirements during the development phase. The CIMOSA diagrams created in Chapter 3, section 3.6 were expanded to create a series of program specific operational plans. A formalised method was required to present this information in a graphical based form. As discussed in Chapter 3 the CIMOSA modelling framework utilises some basic concepts from the unified modelling language (UML)(Fowler, 2004) to create semantically precise process models. Therefore a UML approach was selected to produce a set of meaningful, low level software process diagrams. UML has been widely used as a graphical method for representing software. This methodology includes a broad range of diagrams (e.g. class diagrams, sequence diagrams, object diagrams, activity diagrams) for representing a wide range of operational aspects using well defined modelling notation.

During the development of the low level control software, UML activity diagrams were created to represent the function of each program. These particular models are constructed from the fundamental actions of each program. The actions are linked to indicate the logical flow between them and thus provide a visual representation of the overall behaviour. The illustrations helped to define the different program activities and identify a list of signals and events that would cause a change from one activity to the next.

5.3.1 E_STOPS

As discussed in section 5.2 the E_STOPS program has a number of essential functions in the motion controller. The diagram shown in Figure 5.4 represents the program process flow from the point at which the program is activated. From the "initial node" the program declares global and local variables before automatically initialising the basic communication (i.e. CAN_CTRL) and monitoring programs (i.e MONITOR). The code has been developed to check that only one exercise specific program is operating at any given time by checking the current program status. This ensures that there are no resource conflicts and the variables are configured correctly for the particular exercise.

If there are no exercise programs running, E_STOPS will check the status of the module attachment mechanism to ensure that the attachment is locked in position. The program will also check that the attachment identification code matches the exercise selected. If the identifier is not correct or there is no signal present, E_STOPS flags the HMI to inform the user and waits until the correct setup is achieved. Once the hardware has been configured correctly the user must activate the grip sensor, discussed in Chapter 4, and position the actuator within the limit stops. E_STOPS also checks that the system is set to idle to ensure that no move commands are stored in the controller memory. If the correct signals are received, the program will activate M_SETUP as discussed in section 5.2 and wait for a run program prompt from the HMI. Once a trigger is sent, the exercise program will run until it completes successfully or a local error is detected. Either scenario will cause the program to cancel any stored moves and close. E_STOPS will then require the user to reselect the exercise program and repeat the setup process or choose a different routine.

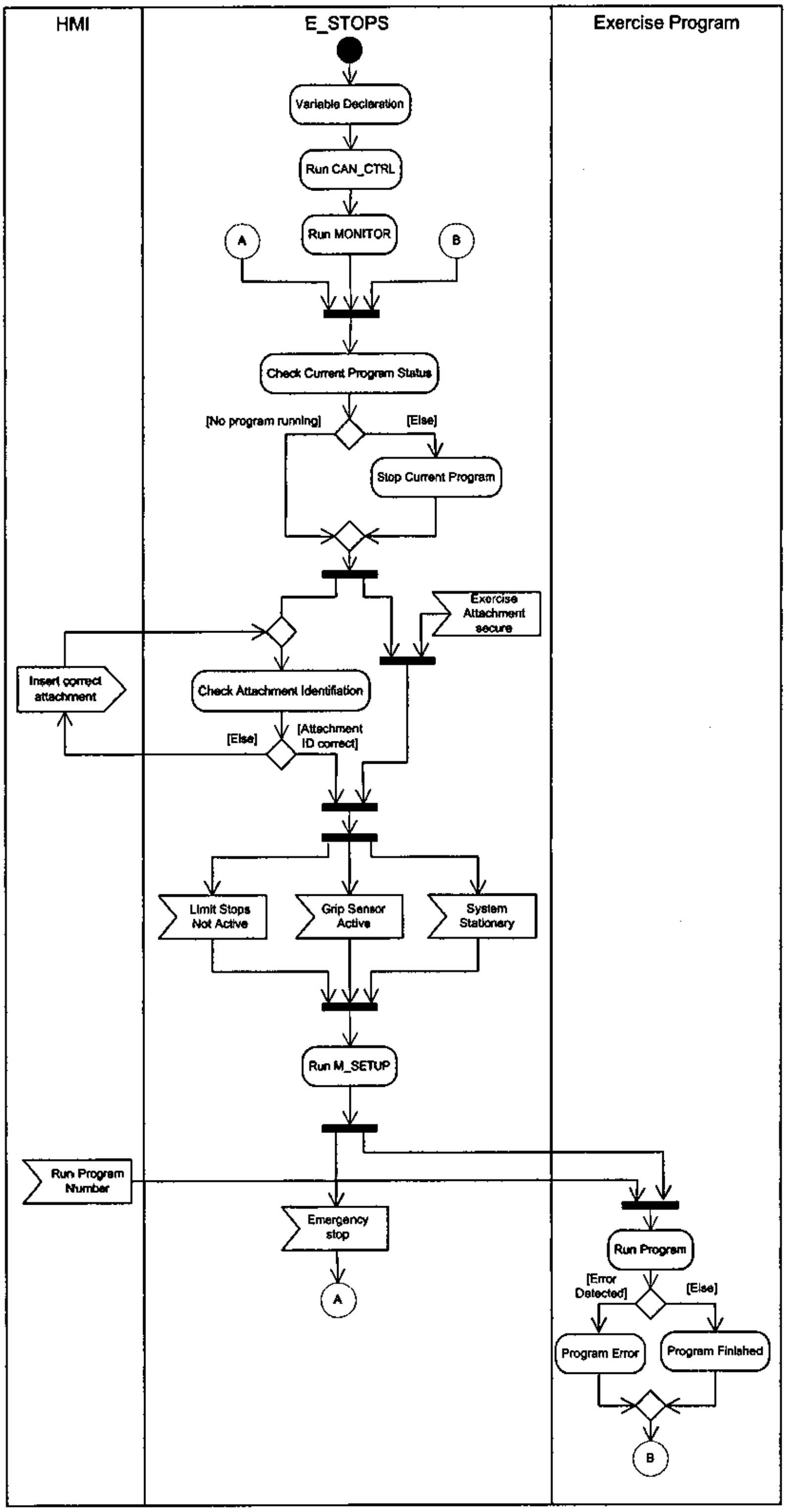


Figure 5.4: UML activity diagram representing the operation of the E_STOPS program.

If, at any point, the output signals from the grip pressure sensor drop below the predetermined level, E_STOPS will implement a control stop procedure. The exercise program currently running is forced into a holding state until the correct sensor outputs are received. Once the user has returned to a safe working position, the particular exercise program will continue as before. If any other emergency signal is received i.e. the user presses the emergency stop button on the high level software, activates the mechanical emergency stop or one of the micro-switches in the limit stop device (see Chapter 4) are activated, then E_STOPS will immediately terminate any active exercise program. This termination procedure cancels all drive commands and deactivates the servo control causing the transmission system to become completely demobilized. The program will return to the system inspection process to ensure that safety systems have been reset and the control parameters are configured correctly before allowing an exercise program to be initiated.

5.3.2 ZERO_SETUP

A series of initial setup procedures have been designed to ensure that the system is configured correctly for each user regardless of their previous exercise experience and knowledge of the equipment. The first operation that the user must complete when using the unit is the "zero setup" procedure. This program is designed to position the actuator in the correct anatomical position for the muscle group selected and provide the motion controller with an absolute zero reference point from which to measure all positional data.

The operation procedure for ZERO_SETUP is illustrated in Figure 5.5. Upon initial activation the program is in an idle state, the local and global variables are declared and the HMI prompts the user to insert one of the mechanical location pins in the zero set-up hole. The actuator may need to be repositioned upwards or downwards depending upon the final positon set by the previous user and also the configuration requirements for the particular muscle group selected. The program monitors the direction of the actuator and transmits this information to the HMI. During the zero setup process the resistance system operates in an inert monitoring state, no force is applied to the actuator so the user's movement is completely unrestricted.

The user is instructed to rotate the actuator until the location pin strikes the limit stop device. At this point the micro-switch is activated and the program detects this signal as conformation that the zero position has been achieved. The system immediately stores this position as the datum point for all further exercises and sends a notification signal to the HMI. Once the zero position has been set, the program resets the upper and lower limits stored in the controllers local memory, automatically closes and the HMI prompts the user to continue with the next setup stage.

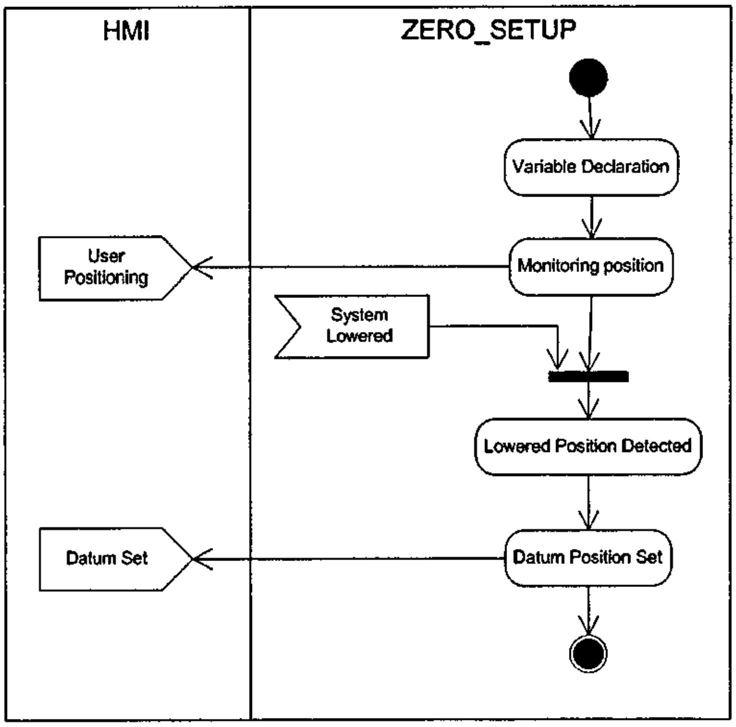


Figure 5.5: UML activity diagram representing the operation of the ZERO_SETUP program.

5.3.3 RANGE_SETUP

Having established a zero position, the user must then record their maximum range of motion. This information is used to prevent the user from exceeding their current level of flexibility and acts as a set of "virtual e-stops" which are used in subsequent programs. The user is instructed to complete three basic lifting motions over the widest range of movement that they can achieve.

To ensure the absolute safety, the user is required to insert the location pins of the limit stop device in a specific pattern which corresponds to their maximum range of motion for that joint. Also the program constantly monitors the position to ensure that a predefined set of safety e-stops are not exceeded for that group of muscles. If the physical or virtual stops are activated, the resistance is applied to prevent the user from hyperextension or other injury. In order to continue, the user must return the actuator to the lowered start position before the system will allow the repetition to be repeated or, alternatively, the user may choose to start a completely new set.

The RANGE_SETUP program (see Figure 5.6) monitors the position of the actuator and performs a series of comparisons in order to determine the maximum and minimum positions achieved. If the system detects that the direction of rotation of the actuator has switched, the position of this transition will be recorded. If no change is detected during the process cycle time, the program will continue to loop around the monitoring sub-routine. The user is prompted by the HMI to begin the activity with the actuator held in the lowest point permitted anatomically, thus the first reversal is assumed to represent the upper limit. The user must complete three repetitions, where one repetition constitutes one raising and one lowering movement, in order to complete the exercise.

The limits of motion for each repetition are stored and an average calculated to determine the overall operational range. In order to prevent the recording of erroneous or non-representative values, a positional threshold has been specified. The three data points must be within a predefined boundary (i.e. five degrees) before the final value is calculated. If the distribution of the values is too great, the user will be instructed to repeat the process. Once the upper and lower limits have been calculated, they are stored as a pair of global variables for use by the other exercise programs and published to the HMI. Once the user has confirmed that the calculated range of motion is acceptable, the program terminates.

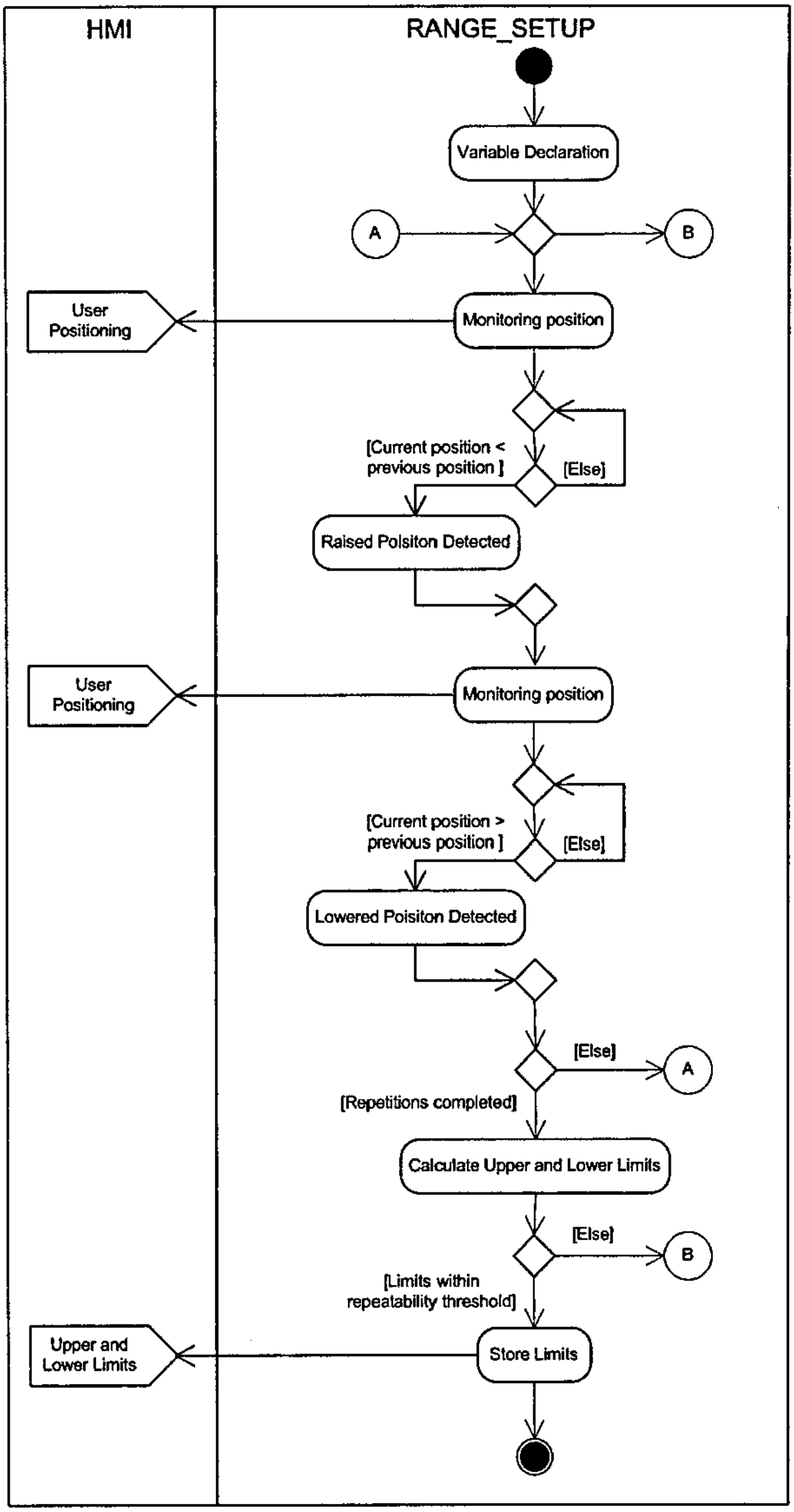


Figure 5.6: UML activity diagram representing the operation of the RANGE_SETUP program.

5.3.4 ISOMETRIC

ISOMETRIC is the first of four primary resistance programs which have been created to replicate and enhance existing exercise modes both for testing and training purposes. ISOMETRIC refers to a stationary contraction during which the length of the muscle does not vary. Each of these exercise programs have been developed with a default set of parameters which are based on current research and practical knowledge established throughout the training community. If the user has limited training experience or simply has no interest or time to consider the exercise details, then these basic training systems provide a simple, easy to follow regime.

The exact configuration options for each exercise will depend upon the users training history and status, such that an experienced individual will have the authority to adjust a wide range of exercise parameters (e.g. weight, number of repetitions, training routine, profiled loading) to suit their precise training requirements while a novice user may be restricted to prevent serious injury. The ISOMETRIC program has a standard process which is detailed in Figure 5.7.

Once the user has selected an isometric exercise, the program will declare its variables and default parameters before waiting for the user to accept the default settings or enter their personal preferences in the HMI. Once the required number of repetitions has been received, the actuator can be moved to the start position. During this initial set-up phase, changes in the actuator position are monitored using a standard sub-routine "Set Position", which is common to all of the exercise programs, shown in Figure 5.8.

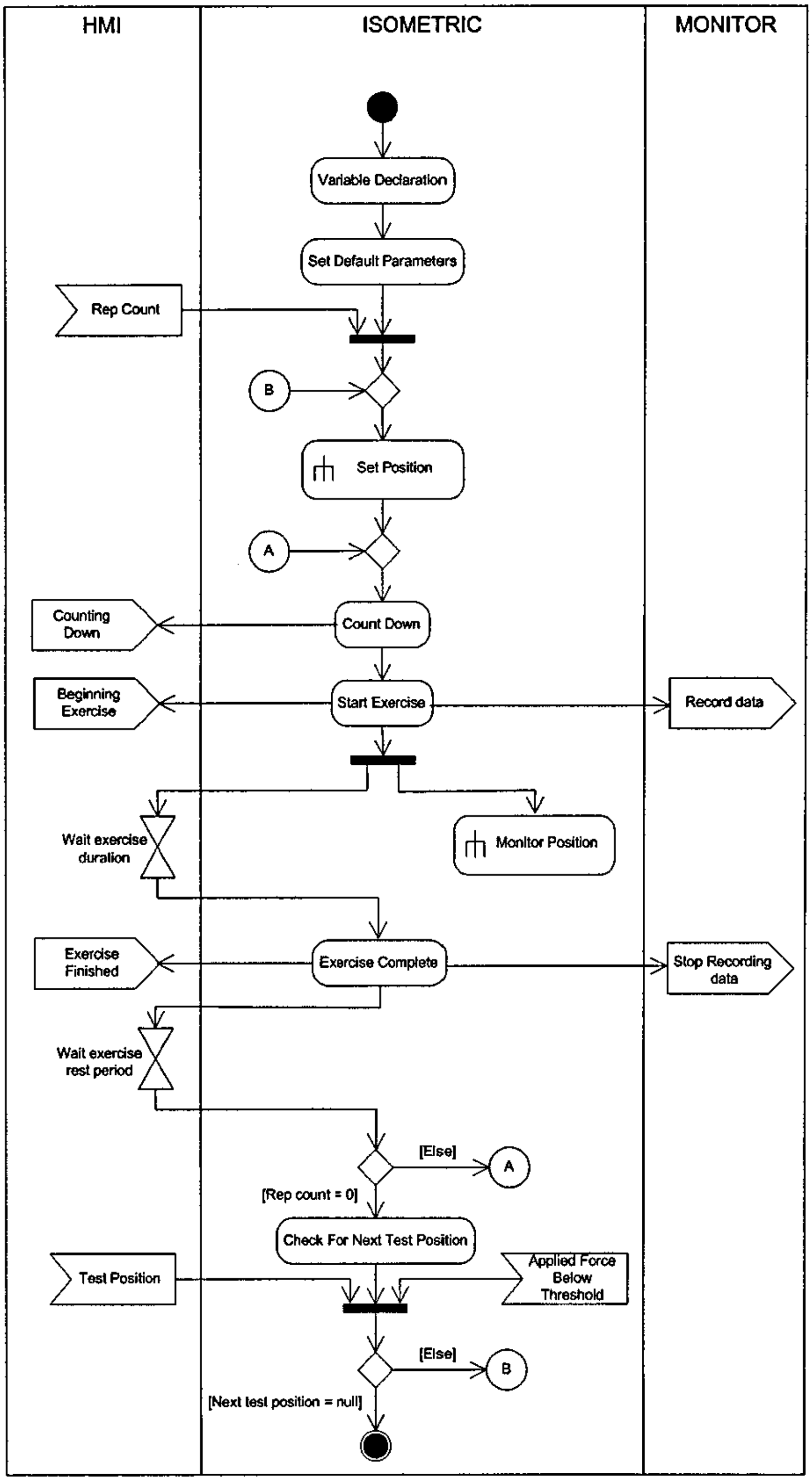


Figure 5.7: UML activity diagram representing the operation of the ISOMETRIC program.

The system monitors the current position and its relation to the start point in order to advise the user on which direction to move the actuator. At this stage, the resistance system is not active and the user is free to move the system without any restriction. Once the correct position has been achieved within a specified tolerance (± five degrees), the user is alerted via audio and visual messages in the HMI. The actuator must remain stationary within this tolerance band for one second before the position is accepted and the resistance system is activated. The system will then drive the actuator at slow speed to the final start position. This secondary positioning procedure improves accuracy and repeatability which could not be guaranteed using a purely manual location process.

At each of the specified positions the user will conduct a series of exercise repetitions and rest periods before moving to the next nominated point. The system provides the user with a simple count down to signify the start of the exercise and also highlights the time remaining. During the exercise, the user is required to produce a maximum force against the stationary actuator for a given time period. An activation signal is passed to the MONITOR program at the start of the exercise to commence data recording. The HMI displays the variation of torque with time and also the repetition average of the maximum torque as a function of position (See Chapter 6, section 6.3.3.4).

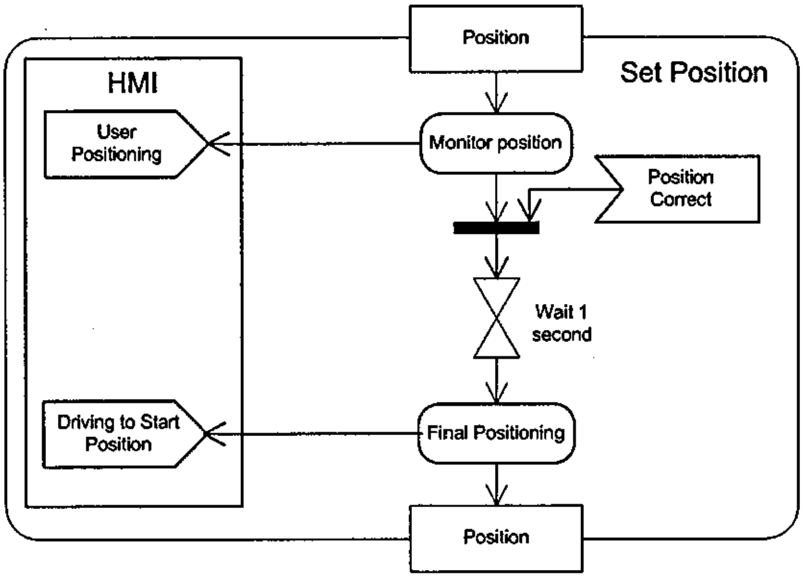


Figure 5.8: UML activity diagram representing the operation of the Set Position sub-program.

Each of the exercise programs feature a common position monitoring sub-routine "Monitor Position", as shown in Figure 5.9, which acts as an additional safety system. As discussed previously, the upper and lower movement limits are stored as global variables by the RANGE_SETUP program. This information is then used by the active program to determine virtual e-stop positions. When the user is instructed by the HMI to position the limit stop pins in appropriate positions (see Chapter 6, section 6.3.3.3), the system includes a small buffer distance in the calculations. This buffer distance is designed to give the motion controller time to deactivate the resistance system before the physical stops are encountered in the event of a system malfunction. If the user exceeds these limits, having been informed that the maximum safe distance has been achieved, the program terminates the training mode. All move commands are immediately cancelled and the servo drive is disabled. If a limit error is detected, the user must restart the exercise to ensure that the system is reset correctly.

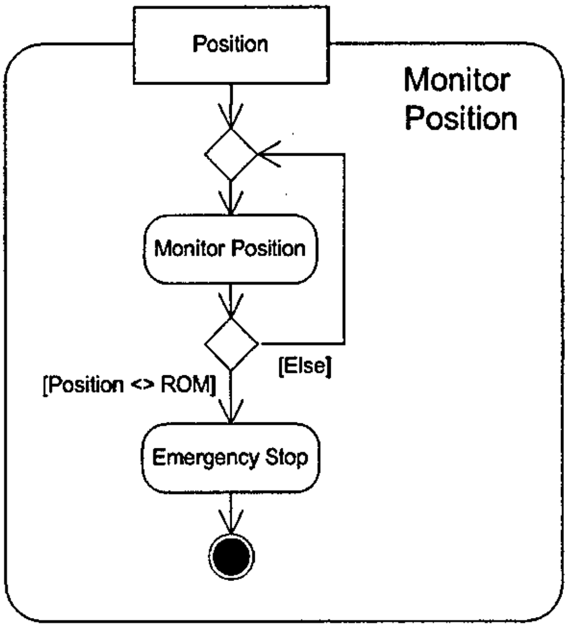


Figure 5.9: UML activity diagram representing the operation of the Monitor Position sub-program.

Once the exercise is complete, the MONITOR program is stopped and the user is allowed to rest for the specified period, before counting down for the next repetition.

If all of the repetitions for that particular position have been completed, the system checks for the next exercise position. If a change in position is required, the user must reduce the force applied to the actuator until it is below a threshold value (i.e. 20 Nm). This prevents a sudden drop in resistance which could cause the user to unexpectedly accelerate the actuator and sustain an injury. Once the system detects the force has reduced sufficiently it will return to the positional control loop and guide the user to the next exercise location. If there are no further positions the program closes and the user interface returns to the exercise selection screen (See Chapter 6, section 6.3.3.2).

5.3.7 ISOKINETIC

An isokinetic movement is conducted at constant speed and thus the ISOKINETIC program (see Figure 5.10) is designed to control a range of exercises during which the velocity between a set of positional limits is maintained at a constant value. The range of motion over which the exercise will be conducted is nominally set to the maximum limits calculated during range setup (see section 5.3.3). The user may exercise over a smaller range then the nominal value but is prevented from exceeding either the higher or lower limits by the software. Depending upon the precise range of motion specified, the user will be prompted to insert the location pins of the limit stop device at the corresponding point in the system.

The user is instructed to position the actuator in the correct position for the range of motion and type of contraction specified using the basic movement program as detailed in section 5.3.4. Once the actuator is locked in the starting position, the system will upload the motion parameters for the initial contraction type selected. If the initial movement is concentric, the user interface will inform the user that the exercise is ready to commence once the preload force has been exceeded. In order to activate the movement, the user must apply a force which is greater then the specified preload value (i.e. 20 Nm). This ensures that the system does not accelerate before the user is fully prepared. During the exercise, the system drives the actuator over the range of motion at a constant speed regardless of the additional input from the user, who is attempting to accelerate (or decelerate depending on the mode of exercise) the system.

If an eccentric contraction has been selected, the user interface provides a visual and audio count down to the start of the exercise. At the end of this count down, the drive system initiates a constant velocity move of the actuator while the user attempts to resist the motion. Once the exercise has been initiated, an activation signal is sent to the MONITOR program and data collection will begin. Regardless of the exercise type, during each move the user must maintain a minimum threshold force during the movement (i.e. 10% of one repetition maximum). If the user can not apply this input magnitude then the system will implement a controlled stop. This reduces the chance of user injury and ensures that the response to training is maximised by promoting a high intensity level.

Once the initial motion is completed, the system may either return to the positioning mode or provide a training motion in the opposite direction. If repeat concentric-concentric or eccentric-eccentric repetitions have been specified, the system will switch to the positional mode to allow the actuator to be returned to the starting position for the next exercise. If a series of concentric-eccentric exercises have been specified, the system simply drives backwards and forwards until the desired number of repetitions have been completed. Once the required number of repetitions has been completed, a confirmation signal is sent to the HMI and the program will wait idle to allow the user to rest until the next exercise can begin.

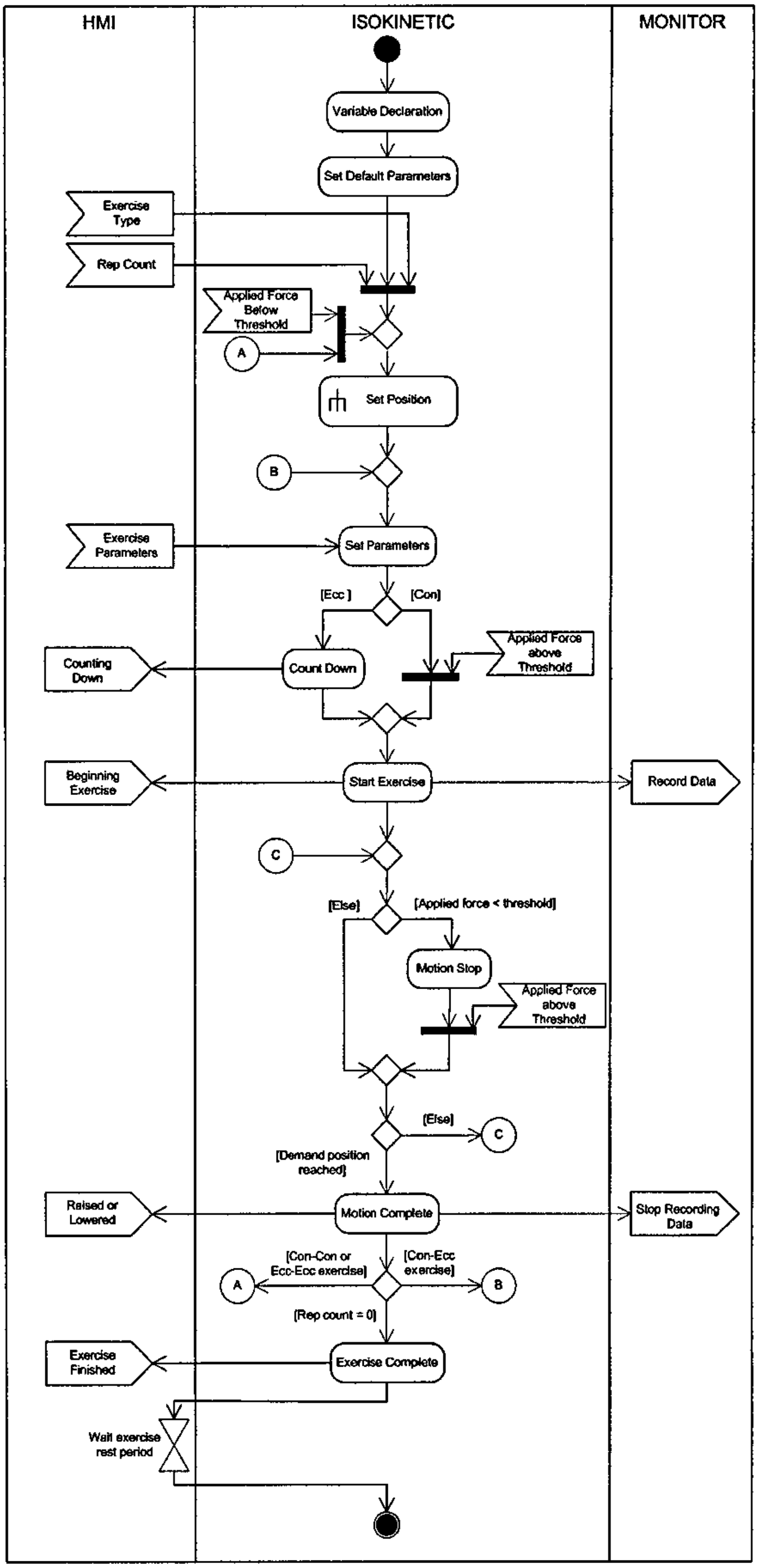


Figure 5.10: UML activity diagram representing the operation of the ISOKINETC program.

5.3.8 ISOTONIC

The ISOTONIC program is designed to replicate the load conditions experience when exercising using a standard set of free weights or selectorised weights machine, with and without inertial effects. This exercise mode uses a torque feedback loop arrangement within the servo drive that is activated via the motion controller, see Figure 5.11. In this mode, the motion controller specifies a torque set point at which the motor will operate. The program also processes and transmits the actual torque experienced by the user as recorded by the torque transducer. The servo drive is pre-programmed with an algorithm to compare each input and feedback signal and adjust the motor response to give a constant torque value.

In this mode, the motion controller acts as a monitoring system for the servo drive. The program structure for the ISOTONIC program is shown in Figure 5.11. At a basic level, the system will allow the user to specify the precise load level, number of repetitions, number of sets and rest periods but will operate and feel like a standard free weight exercise. Experienced users can implement individually profiled load patterns or undertake specific training systems to suit their particular requirements as discussed in Chapter 6.

Customisation of the various exercise parameters does not affect the basic operation of the program, which begins with the simple variable / parameter declaration procedure followed by the positioning sub-routine. Once the desired position has been achieved, the motion controller activates the control loop in the servo drive. If the user is conducting a basic set of lifting exercises, the system waits idle until the user inputs a force which is equal or greater than the specified load. Once the preload has been exceeded, the motor controller attempts to maintain a constant force for the user to exercise against.

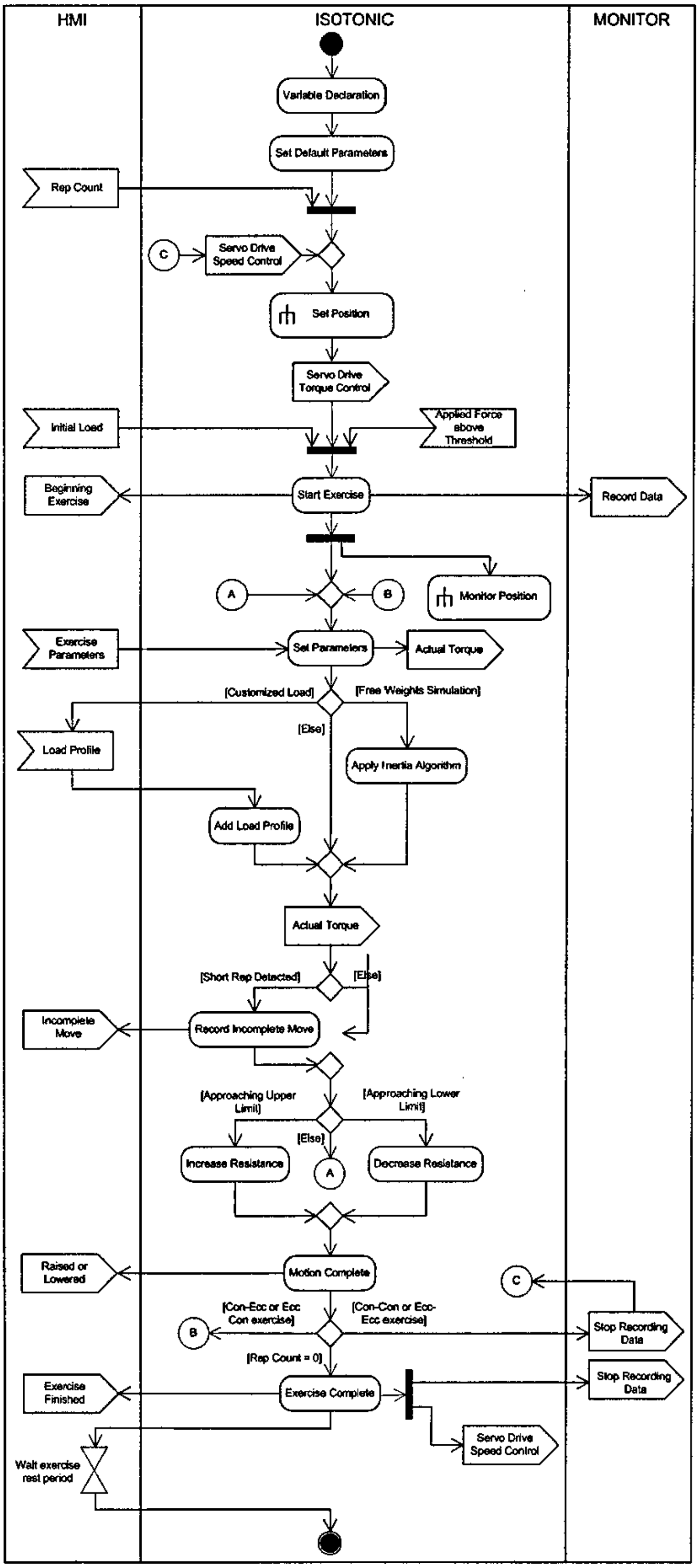


Figure 5.11: UML activity diagram representing the operation of the ISOTONIC program.

The basic control structure of the ISOTONIC program can be used to create a vast range of customised load profiles. These profiles can be created to simulate the force and inertia characteristics of existing resistance training equipment as discussed in Chapter 3 or any other load-position relationship that may be conceived. Each profile is generated using a custom application developed for the HMI (see Chapter 6). This tool allows the user to specify the exact resistance at any point in their range of motion. The profile generation application creates a torque and position reference table such as the simplified example shown in Figure 5.12.

Position (degrees)	Isometric torque (Nm)	Position (degrees)	Isometric torque (Nm)	Position (degrees)	Isometric torque (Nm)
18	29.99	48	37.51	81	33.93
19	30.41	49	37.57	83	33.61
20	30.99	50	37.63	84	33.29
21	31.74	51	37.68	85	32.98
22	32.02	52	37.73	86	32.66
23	32.60	53	37.76	87	32.34
25	33.20	54	37.79	88	32.03
25	33.50	55	37.81	90	31.72
27	34.09	56	37.82	91	31.42
28	34.65	57	37.82	92	31.13
29	34.92	58	37.81	93	30.85
30	35.17	60	37.78	94	30.58
31	35.39	61	37.73	95	[illegible]
32	35.59	62	37.67	96	[illegible]
32	35.77	63	37.59	97	[illegible]
33	35.95	64	37.50	98	29.70
34	36.11	65	37.38	99	29.54
35	36.25	66	37.23	100	29.40
37	36.52	67	37.06	101	29.29
38	36.63	68	36.87	102	29.21
39	36.74	70	36.66	103	29.16
40	36.84	71	36.44	104	29.15
41	36.93	72	36.20	105	29.18
42	37.01	73	35.95	106	29.30
43	37.09	74	35.69	107	29.46
43	37.17	76	35.42	108	29.66
44	37.24	77	35.13	109	29.89
45	37.31	78	34.84	110	30.16
46	37.38	79	34.54	111	30.45
47	37.45	80	34.24	112	30.78

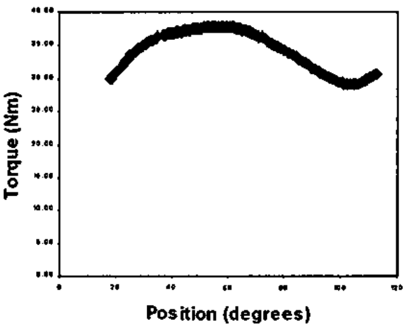


Figure 5.12: Example of an ISOTONIC customised load profile table structure and resultant output.

Once this table has been downloaded to the motion controller, the force profile can be implemented by the ISOTONIC program. During operation the actuator position is constantly sampled and compared to the values stored in the look-up table. The corresponding torque for each position is uploaded every process cycle to the servo drive and the appropriate motor adjustments are made.

If the user would like to train using a simulation of a traditional fixed weight system then the ISOTONIC program will apply a local algorithm to the load profile. This algorithm is designed to replicate the inertia effects experienced when using such systems. Assuming that the mass, m, is applied as a point load, the total torque ,τ_T, that must be applied by the primary resistance system can be expressed by the sum of the load moment and its inertial effect about the centre of rotation. Thus the algorithm can be defined as follows:

$$\tau_T = ((m \times g \times Sin\theta) \times r) + ((\frac{\omega_2 - \omega_1}{dt}) \times (m \times r^2)) \qquad (5.1)$$

Where: m = equivalent mass representing the weight as selected by the user

θ = angular position of the actuator relative to a horizontal datum

r = actuator length

ω_1 = initial velocity

ω_2 = current velocity

dt = sample period

During each repetition, the ISOTONIC program monitors the position of the actuator to determine the direction of travel and verify that a limit has not been reached. If the program detects that the current position is within the perimeter boundaries, the HMI will notify the user that they are approaching the limit of their range of motion. In order to prevent the actuator from activating the limit stops after each cycle, the system modifies the applied load at these peripheral positions. At the upper position the load is increased and conversely, the load is decreased at the lower position. This superposition of safe load profiles at the extremes of motion assists the user in controlling the actuator at these transition points. The user is encouraged to exercise over their full range of motion in order to maximise the training benefits. If the user is unable to reach these target points due to fatigue or any other undue factor, the program will allow the exercise to continue. In the event that a change in direction is detected at an unexpected location, the user is prompted by the HMI to continue in the original direction. If they persist in moving the actuator in the opposite direction, a short repetition will be recorded and highlighted in the data.

If the user has selected a standard resistance training regime, the system will continue to apply the load, although the magnitude may change, and count down each repetition as the actuator is raised and lowered until the specified number have been completed. If a specialist training system has been chosen, the program will stop data recording and return to the positional mode after each repetition to allow the user to train using a single contraction type. Once all of the repetitions have been completed the MONITOR program will be deactivated and the servo drive will be reconfigured to its original speed control settings.

5.3.9 VARIOKINETIC

The principle of the VARIOKINETIC program (see Figure 5.13) is to provide advanced users with the capabilities to train against specific integrated speed and torque profiles. The variables and default parameters are declared initially as per the previous exercise programs. The user is instructed to move the actuator to the start position and the automated sub-routine provides the final position adjustment. The program is ready to begin the exercise and waits for the user to apply a force that is greater then the predefined threshold value. Once this input has been received, the MONITOR program is sent the record data signal, the servo drive is switched to operate in torque control mode and the resistance system begins to apply an initial load.

Before the VARIOKINETIC program is activated, the HMI guides the user through the exercise configuration process which is discussed in detail in Chapter 6, section 6.3.3.3. Using the instructions provided, the user can create two customised profiles: velocity versus position and torque versus position. During the exercise, the

VARIOKINETIC program monitors the movement parameters and adjusts the applied load accordingly. If the user is capable of moving the actuator at the demand velocity for the corresponding position then the resistance will not be altered. If at any time, the actual velocity of the actuator rises above or drops below a threshold value of the demand speed, then a proportional scaling factor will be applied to the resistance. If the actual velocity is greater then that specified, the resistance will decrease according to the velocity / torque relationship determined from the users calibration information (see Chapter 6, section 6.3.3.3). If the actual velocity is less then the required value the resistance will be increased using the same correlation process.

Once the correction factor has been calculated the "Set Resistance" sub-routine (see Figure 5.14) assesses the resultant resistance figure to ensure that the rate of change of resistance does not exceed comfortable levels. If the required resistance is sufficiently low, a minimum operational value will be used. If the required resistance is above the minimum level, a comparison is conducted against the torque versus position profile established during the setup procedure. A maximum and minimum deviation tolerance is placed on the demand profile to prevent excessive rates of change and ensure that the basic exercise characteristics are maintained. If the required resistance is within the tolerance band then this value will be accepted and the load will be adjusted accordingly. Resistances which exceed the tolerance band will be restricted to the maximum or minimum deviations permitted for the exercise. These constrained values will then be used as the demand load.

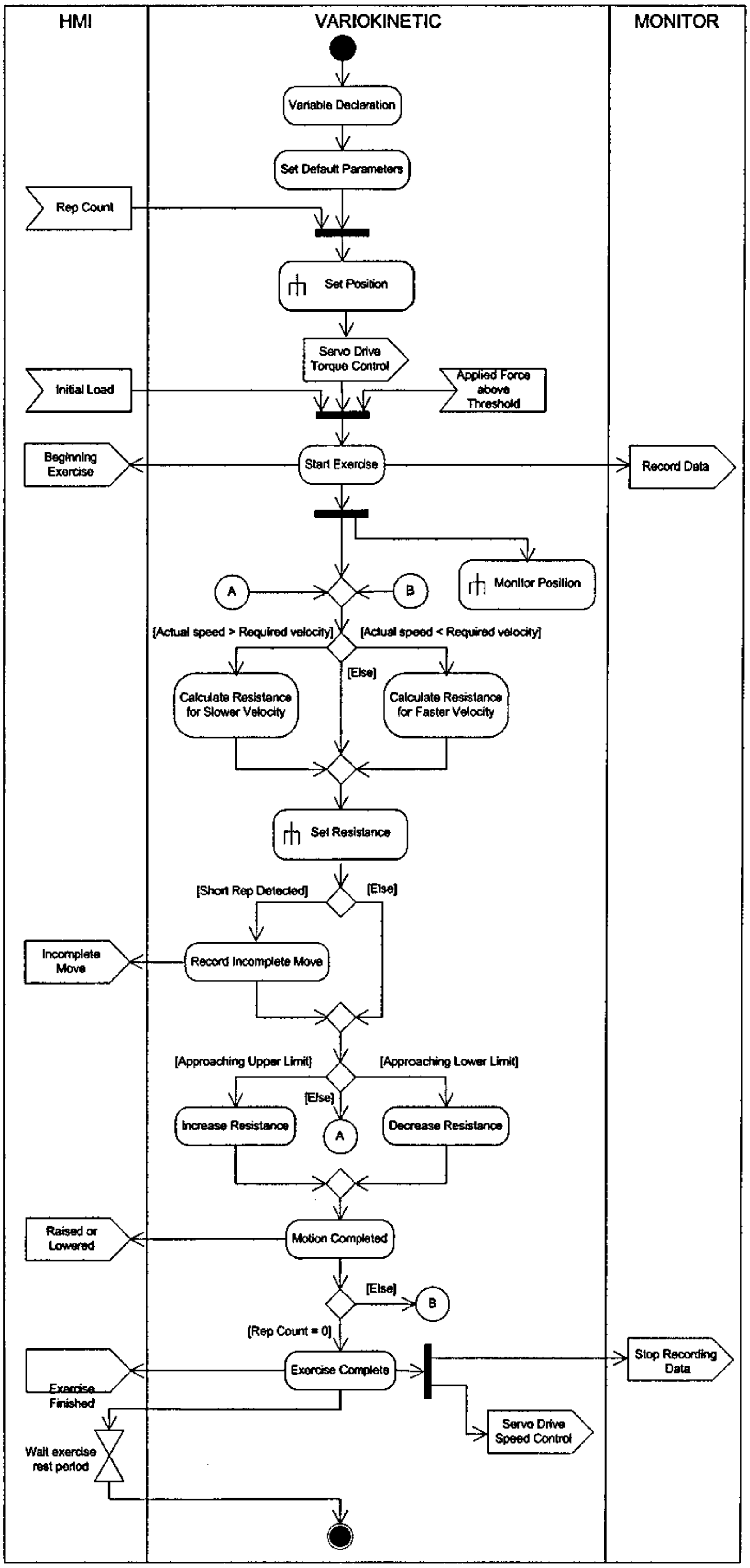


Figure 5.13: UML activity diagram representing the operation of the VARIOKINETIC program.

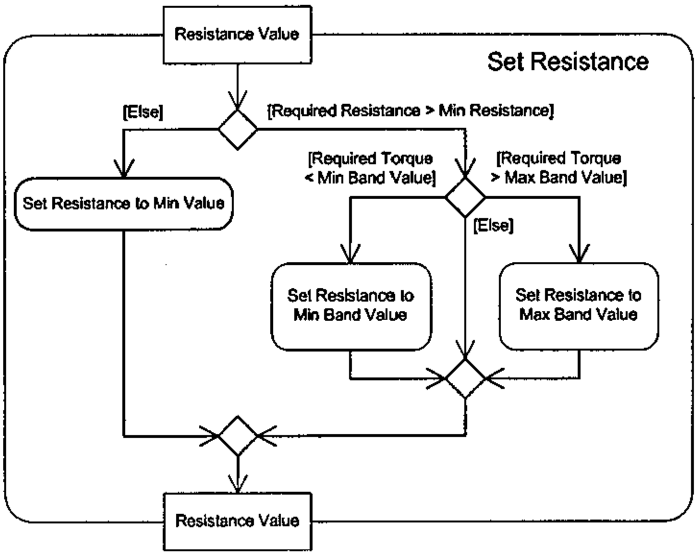


Figure 5.14: UML activity diagram representing the operation of the "Set Resistance" sub-program.

The direction and velocity of the actuator between the upper and lower limits of the user's range of motion is constantly monitored. This information is used in an identical way to that in the ISOTONIC program (Chapter 5, section 5.3.8). The VARIOKINETIC program is able to identify "short repetition" situations when the user has accidentally or consciously failed to move the actuator over the complete exercise distance. Such an event will not cause the program to stop but will be identified in the data during post analysis. This ensures that the user or performance analyst is supplied with accurate information that is representative of the training completed. If the correct range of motion is achieved, the program applies the same load variation as the actuator approaches the limits as found in the ISOTONIC program. Once all of the repetitions have been completed, data recording is cancelled and the servo drive is returned to its previous state.

5.3.9 CYCLE

The CYCLE program has been designed to replicate the operational aspects of modern exercise cycles. As shown in Figure 5.15, and common to all exercise programs, the appropriate variables and parameters are defined at the start of the program. The user must then select a training mode from the HMI before the program will continue. These training modes represent different resistance versus distance relationships which are commonly found on commercial systems. The HMI also provides a set of advanced simulation modes which increase the realism of the training experience (see Chapter 6, section 6.3.3.2) by altering the inertial response of the system to replicate typical cycling experiences.

Once an exercise mode has been selected, the MONITOR program will be initiated and data recording will begin. As the user applies an input to the pedals, the speed at which the resistance system rotates will increase to simulate a standard exercise bike. Acceleration of the system is proportional to the magnitude of the applied force and the effective resistance that has initially been set. During the exercise the resistance will automatically vary to suit the training mode selected but the user may choose to override these settings and alter the level at any point. These adjustments will alter the acceleration response characteristics of the resistance system in relation to the user's effort. Manipulation of the effective resistance using suitable algorithms could allow detailed real-life factors such as terrain and environmental conditions to be included in the training session.

If the user wishes to end the exercise at any time, they can simply reduce the force applied to the pedals such that the system will slow down at a rate representative of the real deceleration rates experienced for the mode selected. Once a sufficiently low speed has been achieved the system will perform a controlled stop. Alternatively the user may activate the emergency stop on the HMI which will implement a swift but restrained deceleration procedure.

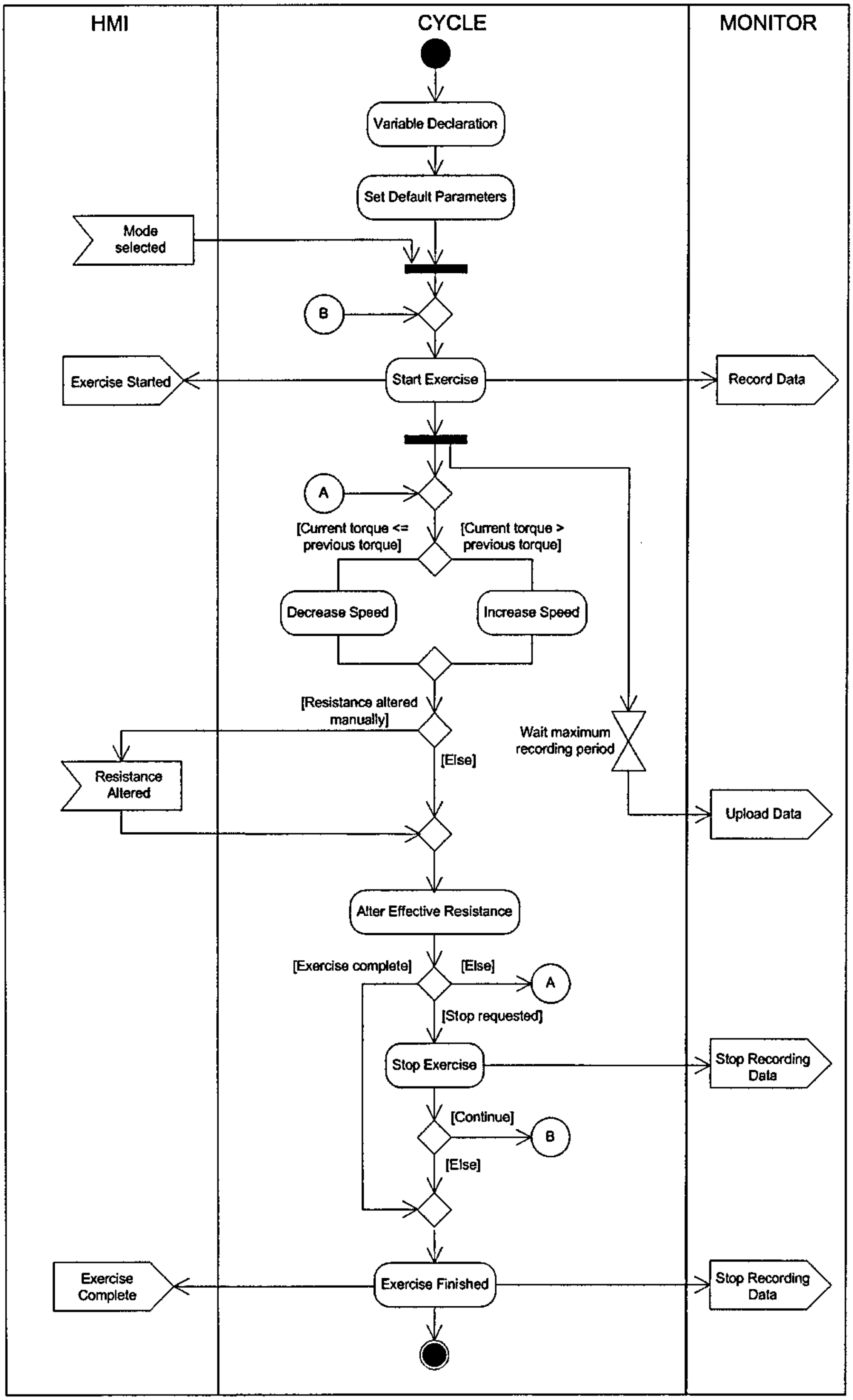


Figure 5.15: UML activity diagram representing the operation of the CYCLE program.

The average exercise duration for aerobic devices such as exercise cycles is considerably longer then that of resistance equipment. Given the limited data storage capabilities of the motion controller it was necessary to provide a synchronised upload procedure to transmit data to the HMI for permanent storage during the exercise process. Depending upon the training mode selected, the user can specify the most appropriate data recording rates. For inter-stroke performance analysis, high capture rates may be used over short periods without the need to upload the information. For long duration stamina training, the program will provide MONITOR with a periodic update signal which will shift live data to a different location and allow the previous array to be uploaded by the HMI. This process will continue until the training distance has been completed. The user will then be instructed to reduce their input and finish whilst data recording is stopped.

5.3 Further developments

Using an active resistance unit such as that found in this system introduces a number of additional safety aspects that are not commonly found with traditional exercise equipment. In order to maximise user comfort, safety and piece of mind, a number of dynamic and passive safety systems have been designed and tested as part of the development process. During this process, a series of advanced software controls were also identified which could implement proactive system changes based upon the user's inputs (e.g. movement speed and applied torque). The underlying concepts are discussed below but have not yet been fully implemented and tested in the prototype system. This intelligent safety functionality will utilise robust pattern recognition algorithms to identify and characterise genuine emergency scenarios without triggering incorrectly during normal exercise movements.

Throughout the various exercises, it would be possible for the software to monitor the user performance data for any unusual or unexpected behaviour. For instance, during an isometric or isokinetic test, a sudden drop in the applied force is likely to represent a situation where the user is encountering some form of difficulty and therefore corrective action should be taken. Alternatively, if the magnitude of the force increases rapidly, the drive system may have struck an object and thus should be deactivated immediately. User fatigue may also be monitored using a set of basic algorithms to determine the minimum safe working level as a percentage of the maximum capabilities established during calibration and the one repetition maximum test (see Chapter 6, section 6.3.3.3). Physiological information could also be integrated into this system to control the level of output based upon critical health related factors such as heart rate.

While training in an isotonic mode, the software could monitor the speed of the exercise. If a rapid increase in downward velocity is detected, commonly caused by fatigue in the user and thus reduced ability to resist the load, the user interface will display a warning before the software automatically reduces the load to prevent potential injury. During the lifting cycle, the system examines the position data for signs that the velocity is approaching zero. If the user can not reach the specified lift point and stalls at a level below that which is deemed unacceptable for a particular time period, then the system will lower the applied load until the user is able to complete the repetition.

5.4 Summary

In order to achieve the required exercise functionality from the servo hardware selected in the Chapter 4, a structured and detailed series of software programs have been created. These programs have been developed using industrial control techniques and existing software modelling approaches in a novel and original application. A fundamental set of control programs were written to form the core operational functions of the system. These key elements specify the basic operational parameters, define the hardware communication protocols and provide essential monitoring facilities. The activation of exercise specific programs is controlled by the central administration programs.

Each of the exercise specific programs has been developed to replicate a particular exercise routine. The code has been developed to allow the user to specify the full range of training variables that would be possible with any existing resistance system. Additional functionality has been incorporated to allow the user to have enhanced levels of control over the characteristics of the actual exercise motion. The performance outputs during these are sampled and stored at sufficiently high data rates to ensure that the information is suitable for academic and clinical research.

Safety is a major concern with an active resistance element such as that used in this exercise system. In order to comply with all of the relevant standards and ensure the user is comfortable with the operation of the system, a number of passive and active safety features were incorporated into the software code. Some of these features are triggered by simple emergency signals while others monitor different user inputs and system parameters for signs of irregular behaviour and take action accordingly. When integrated with the specified hardware systems, these software-based solutions ensure that the user is not only fully protected in the event of a system failure but also monitored to prevent exercise-induced injuries.

Chapter 6

Human-machine interface design

6.0 Introduction

The inclusion of an electronic user interface to provide performance feedback and monitoring in modern exercise equipment is becoming a standard feature. These systems are designed to convert the low-level operational signals and commands into a meaningful format that any inexperienced user could understand without the need for formal training. Exercise system human-machine interfaces (HMI) provide information and guidance for the user when configuring the equipment and present real time data in a clear and concise format during the exercise. Post-exercise analysis capabilities and long term data storage facilities may also be initiated via these electronic interfaces. The main interface components and their interaction with the other components of the modular exercise system are highlighted in Figure 6.1.

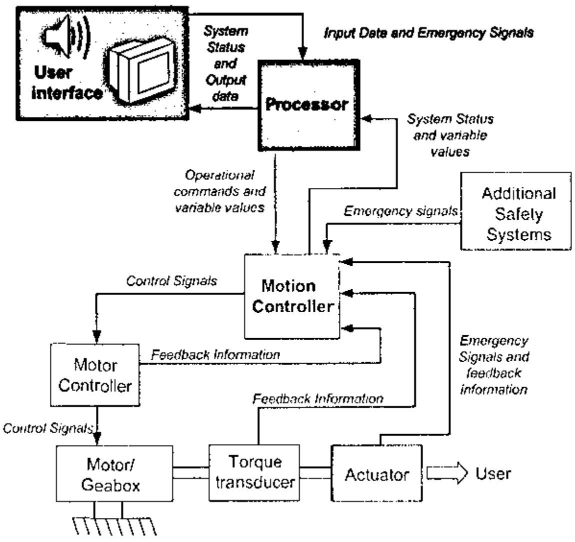


Figure 6.1: Schematic of the main interface components and their interaction with the other system elements.

In this configuration the human-machine interface is developed on a standard PC that provides visual and audio output and allows the user to navigate through the system using a mouse or other pointer device. The interface must provide the user with the relevant training information in an effective and easy to operate solution. The development of the user interface for the exercise system followed the process illustrated in Figure 6.2.

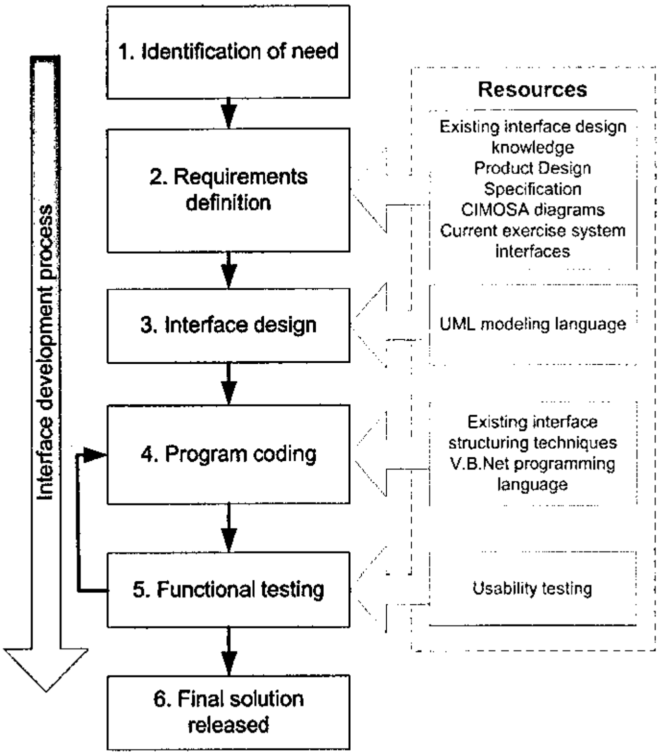


Figure 6.2: Details of the exercise interface development process.

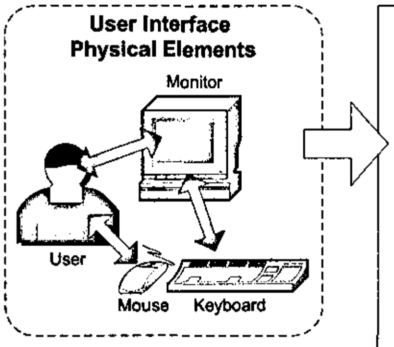
The need for an advanced user interface was identified during the initial research stages of the investigation. Using the product design specification (see Appendix A), existing knowledge of successful interface design, commercial exercise system interfaces and the CIMOSA diagrams discussed in Chapter 3, a detailed set of requirements were identified for the proposed interface. These requirements could then be organised using the unified modelling language (UML) concepts to produce a behavioural map of the system. This set of formalised processes was then structured and coded into an appropriate programming language (Visual Basic.NET (Francesco, 2004)). The initial program code was subsequently tested to evaluate robustness and usability before any necessary changes were implemented and a final interface solution released for integration in the exercise system.

6.1 Interface requirements

The PDS was used to determine the basic operations of the software. The solution would need to communicate with the low-level control programs (see Chapter 5) and utilise a simple display structure to allow untrained users to control and monitor the specialist hardware components during the exercises identified. Safety was a crucial requirement identified from the PDS document. The interface was designed to prevent the user from making decisions that could potentially result in personal injury or damage to the equipment.

6.1.1 Documented aspects of successful user interfaces

In order to develop a successful interface for the modular exercise system, it was necessary to evaluate the underlying theory in software interface design. Spolsky (Spolsky, 2001) stated that, "User Interface is important because it affects the feelings, the emotions, and the mood of your users." The operation and motivational effects of interface design for fitness equipment has been shown to be a critical factor in exercise participation, user commitment and maximum performance (Annesi, 2001). Therefore, the development of a well conceived and executed interface is critical to the adoption of a new exercise system regardless of any advanced hardware capabilities and additional functionality. Development of an inferior interface will detrimentally affect a user's perception of their training program and the equipment. Figure 6.3 summarises the general considerations that should be adhered to when developing a user interface.



Desirable Interface Design Features

- Maximize consistency
- Provide flexibility
- Use metaphors and affordances carefully
- Utilize clear, unambiguous text, images, animations and sounds
- Minimize user decisions/ memory load
- Simplify data entry requirements
- Accommodate all potential users
- Provide informative feedback
- Minimize the opportunity for user errors
- Provide action reversal
- Emphasize sequential, intuitive processes
- Facilitate cross format data import/export

Figure 6.3: Summary of design attributes for an effective HMI.

Consistency is widely regarded as one of the most important considerations when developing an interface as it is applicable to many facets of the design (Schneiderman & Plaisant, 2004). A consistent theme including colour, layout, font style, size and position should be maintained throughout the various screens. The sequencing of these screens during different operations should follow a similar flow and the inputs to progress through these tasks should be consistent. Maintaining a high level of regularity in this manner, allows a user to become comfortable with the operation of the system by using previous experience as a guide to complete unfamiliar functions.

The need to include flexibility in an interface can be considered as contradictory to the concept of consistency. However, many modern interfaces now include an element of customisation which allows the user to alter the presentation of information and system functions. Although the concept of interface reconfiguration is becoming increasing important, the underlying functions and processes below these superficial graphical constructs must be consistent. If flexibility is introduced into a system, then the software must be designed to ensure that users can transform the interface to suit their preferences quickly and efficiently. This may involve some standardised method for loading, saving, transporting and sharing configuration files. As the level of customisation increases, general usability decreases and therefore it is important that the reconfiguration process is as simple as possible.

Metaphors or affordances can be identified in nearly all human machine interfaces (Spolsky, 2001). Metaphors relate program functions to meaningful symbols whilst affordances are elements that inherently suggest a particular function purely through appearance (i.e. shaded buttons to create a 3D appearance). Using graphical representations in this manner ensures that the screen layout is not excessively filled with text and improves the initial discoverability of an interface for new users. When generating graphical metaphoric symbols, animations, general illustrations and text it is important to consider the colour, size and position of each element. For functional elements colour and size can be used to emphasise important aspects but should not be used exclusively when distinguishing between different information sources (Schneiderman & Plaisant, 2004). Complex illustrations and animations must be clear and unambiguous and only be used where basic symbols and text are inappropriate.

In general the number of choices that are presented to the user should be minimised. Fundamental decisions that must be made to produce the basic functionality can not be avoided. The amount of information that the user requires to make an informed decision should also be minimised and interrelated questions should be ordered sequentially were possible (Schneiderman & Plaisant, 2004). If the user is required to input information then this procedure should be as simple as possible using restricted ranges, pre-selected values and graphical representations. Additional options and input commands which are not related to the core process should not interfere with the main task unless the user actively requests these features.

When developing an interface it is essential to consider all of the potential users of the system (Spolsky, 2001). Different users will require differing levels of information and functionality based upon their experience, age, and system usage. The concept of system flexibility discussed previously could be evolved to include the creation of a number of operational modes which relate to the different users groups. Using this modal approach, the input of data, system control and information extraction can be tailored to suit the individual needs. In the context of an exercise system the spread of user demographics may stretch from elite coaches and medical professionals to untrained, unsupervised individuals and therefore it is important to adjust the interface to correspond to the user requirements and capabilities.

Feedback can often be a key factor in a user's perception of the intuitiveness of a system and also decrease the number of errors (Nielsen, 1993). Every action that the user conducts should result in some form of visual or audio feedback. Feedback should be concise, consistent and appropriate yet not imposing as this will deter a user from using the system. Although system feedback can help to minimise the number of errors that a user encounters it can also be appropriate to include active error avoidance. Errors in selection, data entry and subsequent rectification can be a major factor in user frustration and reduced usability. Erroneous actions should be removed by constraining inputs or selections where possible. If appropriate avoidance methods can not be included, the interface must detect the error and provide concise and clear information for resolving the problem. If an action has been initiated unintentionally, the interference should allow the user to return to the previous stage without having to continue. The ability to rectify errors and change decisions reduces the consequences of the user's actions and therefore increases the level of confidence.

The main functional steps must be organised in a simple, intuitive manner. As the user is guided through the interface, a logical progression must be established from start to finish. This sequential characteristic should be replicated in all of the core activities to increase consistency. Once a process has been completed, the user should be provided with a clear indication that current task is finished and a new one can begin. Compatibility with existing data types provides the user with the freedom to utilise previous records and results in the new interface whilst allowing removal of information for remote analysis and storage.

6.1.2 Existing exercise systems human machine-interfaces

Traditionally, commercial fitness equipment featured rudimentary interfaces using Light Emitting Diodes (LED's) or basic Liquid Crystal Displays (LCD's). These types of interface are still found on inexpensive home fitness equipment including exercise cycles, rowing machines, elliptical trainers and treadmills. In this environment, the basic monitoring facilities and uncomplicated operation have been widely adopted as users are not intimidated by the technology. However, there has been a migration in commercial gym equipment away from these primitive designs towards more advanced, interactive interfaces.

A comparative illustration of two interfaces taken from identical aerobic training devices (Lifefitness recumbent cycles) is given in Figure 6.4. The traditional interface features a series of fixed performance measures which are presented using a simple alphanumeric LED display. Information regarding time, speed, distance, calories, heart rate and training is provided. However, the values displayed by the interface do not indicate the relative measurement units and the resulting ambiguity could restrict the transfer of results. Ideally all feedback should be accompanied by a suitable unit. The performance register is supported by a secondary LED display which provides a graphical representation of the training routine selected. Additional exercise advice is provided by a simple table and straightforward illustrations which are printed directly on the unit. The system is controlled using a cluster of functional buttons that feature descriptive text rather then metaphoric symbols.

Figure 6.4: Existing aerobic equipment interfaces and key design features.

The second interface shown in Figure 6.4 represents the state of the art in commercial systems. A fully integrated colour touch screen has replaced the simple LED displays of the previous example. This multi-function device provides performance feedback, exercise details, training advice and multimedia entertainment in a single dedicated unit. The interactive system allows the user to input the initial exercise parameters (e.g. distance, interval time) through the screen but also features real-time resistance control capabilities. This active adjustment is achieved using a set of multi-function "soft keys" as commonly found on modern mobile phones and personal organisation devices. The output of these buttons is not rigidly assigned but alters according to the information on-screen. A limited set of electronic buttons is included to perform the fundamental system functions and external screen controls. Although the system provides many advanced facilities there are no options for customising any aspects of the interface.

The technological advancement of aerobic exercise interfaces, from industrial machine controls towards multimedia entertainment and monitoring centres, can clearly be seen in the product portfolios of major gym equipment manufacturers. In comparison however, the development of similar interfaces for resistance exercise devices is relatively limited. Although the need for external stimuli to maintain concentration and avoid monotony is reduced during resistance training due to the short periods of exertion, some form of motivational / performance feedback can improve performance (Annesi, 2001). Commercial resistance equipment interfaces, which replicate the existing aerobic LED displays, have been introduced into professional gym equipment such as the Technogym Personal Selection equipment. These systems allow training plans and performance data to be stored on a portable device which can be connected to and transported between the various resistance training apparatus. The information recorded during a session can be analysed using a specialist's console or personal computer with the appropriate software installed. Fully integrated PC based interfaces for both monitoring and configuration have been used on resistance dynamometers (see Chapter 2) although these systems are configured for medical / academic operators and do not provide motivational output.

From this review it was clear that standard PC hardware would be ideally suited to the creation and operation of an interface for the proposed exercise system. A solution which permits the inclusion of both active control capabilities and feedback in a single element is required. By using an established hardware platform, the interface could be developed quickly and alterations could be made relatively easily. Additional entertainment functions could be embedded within the main interface structure allowing the effects of such sensory inputs on resistance performance to be analysed in increased depth.

6.1.3 Using CIMOSA models in the HMI specification

The CIMOSA process modelling diagrams created in Chapter 3 were used to determine the activities and information resources that should be included in the exercise system. The activity diagrams, in particular, provide a highly detailed view of the required operation of the system (see Appendix B). The resources and activities identified in the model and the relationships between these elements were used to create the formalised behaviour models discussed below in section 6.2.

6.2 Formalised behaviour documentation

The HMI requirements outlined in section 6.1 were used as guidance for specifying the general appearance, function and input / output capabilities of the interface. In order to develop a suitable program efficiently, the precise step by step behaviour of the system was modelled. Unified modelling language (UML) use cases were selected for capturing the functional requirements of the system. This approach allows the interactions between the interface and user to be identified and documented in a standardised format which is widely recognised by academic and industrial software developers. These use case diagrams were created using knowledge from the general interface requirements and the CIMOSA diagrams. Each diagram is presented as a basic textual list which clearly identifies the fundamental steps which must be undertaken to complete each of the main operational processes. The principal task sequences are referred to (in UML modelling) as the main success scenario (MSS). Additional decisions and processes that can be initiated by the user which result in a deviation from the MSS are recorded below the primary diagram and are referred to as scenario extensions (Fowler, 2004).

6.2.1 Use case - Log In

In order to facilitate interface customisation, training program specification and remote performance monitoring a method for identifying each user and storing the associated data was required. The use case diagram for logging user details at the start of an exercise session is shown in Figure 6.5. It was envisioned that the various system configuration files and exercise related parameters would be stored on a portable device to allow the user to transfer this information between multiple systems. To initiate the system the user must insert this storage device into a suitable connection point on the machine. The system will then examine the attached key for the relevant information. Once the appropriate files have been identified, the system will accept the user as a registered member and upload the necessary configuration data. The user will then be granted access to the system.

Log In

Main Success Scenario:
1. Operator connects storage device to machine
2. System examines user data
3. System accepts registered user
4. System presents exercise selection user control

Extensions:
3a: Operator is a new user
  .1 Operator or system administrator connects a new storage device
  .2 Operator or system administrator starts registration application
  .3 Operator or system administrator completes registration process
  .4 System stores registration data on new device
  .5 Operator or system administrator exits the registration application
  .6 System returns to MSS at step 2
3b: Error reading user key
  .1 System administrator starts registration application
  .2 System administrator checks registration details
  .3 System overwrites registration data on storage device
  .4 System returns to MSS at step 2

Figure 6.5: UML use case diagram for the system log in procedure.

If the user has not been previously registered with the system, a new account must be created for them on a compatible storage device. The user or a system administrator must connect the storage device to the system and open a dedicated registration application. This program requests the basic information to create a user account and allows the operator to enter additional details if they desire. Once the basic data entry process has been completed, the relevant files are downloaded to the storage device. The user will now be automatically identified as a registered member and can access the exercise program. If the user inserts their storage device but is denied access, the registration application can also be used to analyse the data files for potential errors or conflicts. Where possible, problems with the stored information should be rectified and updated. However, the registration application will also provide the facility to completely erase the existing details and re-install the parameters if necessary.

6.2.2 Use case – Select an exercise

Once a user has logged in successfully they must select the desired exercise and configure the hardware correctly as shown in Figure 6.6. The system detects the current setup and identifies this on the interface. If this configuration matches the users training requirements the exercise can be selected. Assuming that the system is configured for a resistance exercise the user will be required to select a muscle group to exercise. A secondary hardware check is conducted to ensure that the hardware is arranged appropriately and the correct exercise attachment is installed. If system hardware confirmation is received, the interface will display the exercise mode options. If the user has made an erroneous decision during the selection process, an appropriate facility should be made to allow them to return to the previous screen.

Select an Exercise

Main Success Scenario:
1. Operator or training advisor selects the desired exercise type
2. System checks the hardware configuration and identifies current setup
3. System accepts the required exercise
4. Operator or training advisor selects a muscle group to exercise
5. System conducts secondary hardware configuration check
6. System accepts the required muscle group
7. System displays the exercise mode user control

Extensions:
1a: Operator or training advisor selects an aerobic exercise
    .1 System checks the hardware configuration
    .2 Operator confirms hardware configuration changes
    .3 System automatically adjusts hardware and displays exercise screen
    .4 Operator or training advisor sets exercise parameters
1b: Operator chooses to evaluate performance
4a: Operator or training advisor wishes to change the exercise type
    .1 Operator or training advisor selects the relevant button
    .2 System returns to the select exercise type user control at MSS step 1
7a: Operator or training advisor wishes to change the muscle group
    .1 Operator or training advisor selects the relevant button
    .2 System returns to the select exercise type user control at MSS step 4

Figure 6.6: UML use case diagram for the exercise selection procedure.

The exercise selection screen will include options to allow the user to conduct an aerobic activity or alternatively analyse their performance. If the user chooses an aerobic training session, the system will check the hardware to ensure that all attachments have been removed before confirming the request. Once verification has been received, the system will automatically adjust the hardware to suit the exercise requested and display the relevant setup screen.

6.2.3 Use case – Configure system

The use case for configuring the system for a given exercise is shown in Figure 6.7. The user is presented with a range of exercise modes as identified during the literature review (see Chapter 1). Once a selection has been made, the system will interrogate the user's storage device to ensure that a valid range of motion and current one repetition maximum (1RM) are present and simultaneously display the exercise prerequisites screen. If these parameters are detected successfully, the user can choose to configure the exercise. An exercise specific configuration screen will be displayed which is automatically loaded with a series of default values. By starting the exercise, it is assumed that the user's actions indicate that they wish to accept these universal figures which are subsequently downloaded to the low level software discussed in Chapter 5. The low level software activates the hardware and reports its status to the interface.

Configure System

Main Success Scenario:
1. Operator or training advisor selects the desired exercise mode
2. System checks storage device for a valid range of motion
3. System checks storage device for a valid 1 repetition max figure
4. System displays the exercise pre-requisites user control
5. Operator or training advisor chooses to set the exercise parameters
6. System displays the exercise configuration use control
7. Operator or training advisor accepts default parameters
8. Operator or training advisor starts the exercise
9. System uploads the exercise parameters and displays the exercise user control

Extensions:
2a: Range of motion not valid or operator is a new user
  .1 System displays instructions for setting the range of motion
  .2 Operator confirms that they understand the instructions
  .3 Operator starts the test and conducts the required number of repetitions
  .4 System displays the average range of motion
  .5 Operator accepts the calculated values and returns to MSS at step 2
3a: Operator is a new user or would like to update their 1 repetition maximum
  .1 System sets the default 1 repetition maximum test protocol.
  .2 Operator starts the exercises
  .3 System applies the necessary exercise motion
  .4 Operator attempts to complete the required number of repetitions
  .5 System calculates the 1 repetition maximum from the operator performance
  .6 Operator accepts the calculated values and returns to MSS at step 3
5a: Operator chooses to select a new exercise
  .1 System returns to select an exercise at MSS step 7
5b: Operator chooses to warm up
  .1 System loads the default warm up procedure
  .2 Operator accepts or adjusts the warm up parameters
  .3 Operator starts the exercise
  .4 System applies the necessary exercise motion
  .5 System notifies the operator that the exercise is complete
  .6 Operator finishes the exercise and returns to MSS at step 3
5c: Operator chooses to calibrate
  .1 System displays instructions for calibrating the operator
  .2 Operator confirms that they understand the instructions
  .3 Operator starts the calibration procedure
  .4 System applies the necessary exercise motion
  .5 System notifies the operator that the calibration is complete
  .6 Operator finishes the exercise and returns to MSS at step 3
7a: Operator or training advisor wishes to enter specific exercise parameters
  .1 Operator or training advisor adjusts the relevant parameters using the associated data entry spaces and/or adjustment tools
  .2 Operator saves the updated configuration or starts the exercise without storing the information.
  .3 System returns to MSS at step 9
8a: Operator selects the stop button
  1. System displays the dialog box
  2. Operator decides whether to continue with the exercise or abort configuration
  3. System returns to MSS at step 6 (continue) or step 4 (abort)

Figure 6.7: UML use case diagram for configuring an exercise.

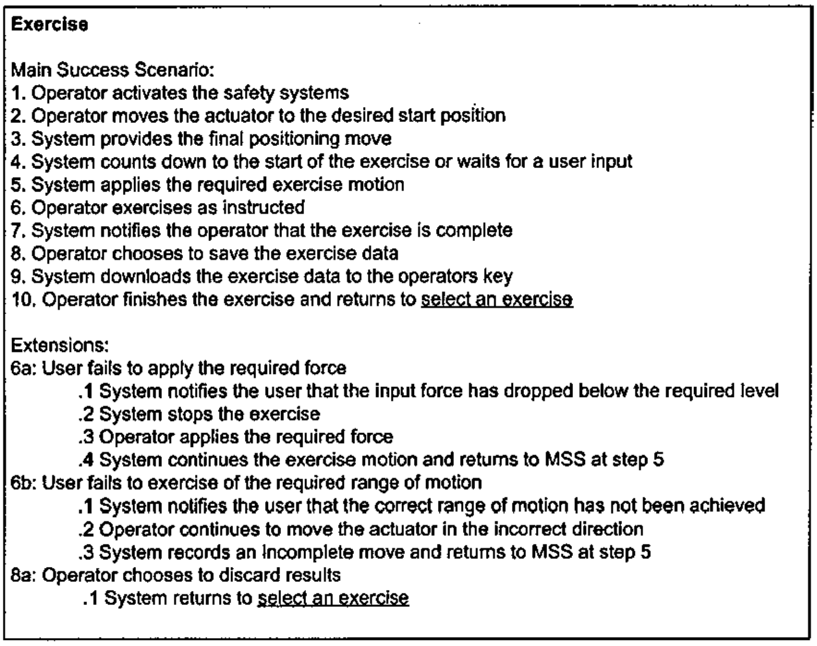
If a suitable range of motion or one repetition maximum figure is not found on the user's storage device or the user would like to update the values, then the system will direct the user through the relevant process. The hardware is configured for the particular test and on-screen instructions are provided for inexperienced users. Upon completion, the data can be saved for reference or the user may choose to repeat the procedure if they are not satisfied with the values attained.

Whilst navigating the exercise prerequisites display, the user may choose to select a different exercise at any point. This option returns the system to the exercise mode selection screen. Other functions which are provided at this stage include a warm-up facility and a calibration regime. The system will assist the user in the completion of an isotonic, low intensity warm-up exercise or provide a standardised isokinetic calibration routine for monitoring performance and training response.

Although a set of default exercise parameters are displayed initially, the user or training operator should be able alter these values to suit the users physiology and training session focus. The customised configuration data can be stored and uploaded automatically in the future if required. Once the exercise parameters have been confirmed and the system has downloaded the values, a stop function is required to terminate the exercise process. If this function is selected, the system will request confirmation that they wish to abort the current exercise configuration or return to the previous screen.

6.2.4 Use case - Exercise

After an exercise has been initiated on the interface, the first step in the exercise use case (see Figure 6.8) is the user activation of the mechanical and electro-mechanical safety systems. The low level software will detect that the necessary interlocks have been made and routinely update the interface with the status of these systems. The interface will prompt the user to move the actuator to the desired start position and provide feedback of the current position. Once the user has positioned the actuator coarsely, the final accurate positioning is to be conducted by the machine. The exercise will commence following an audio and visual count down or will remain stationary until the user provides an input which is above a minimum threshold value. As the system provides the required resistance and movement characteristics the user can exercise as required. Appropriate feedback information is provided by the interface which will notify the user when the desired exercise routine has been completed. The data recorded during the session can be downloaded to the user's storage device or discarded before the system returns to the exercise selection screen.



Exercise

Main Success Scenario:
1. Operator activates the safety systems
2. Operator moves the actuator to the desired start position
3. System provides the final positioning move
4. System counts down to the start of the exercise or waits for a user input
5. System applies the required exercise motion
6. Operator exercises as instructed
7. System notifies the operator that the exercise is complete
8. Operator chooses to save the exercise data
9. System downloads the exercise data to the operators key
10. Operator finishes the exercise and returns to select an exercise

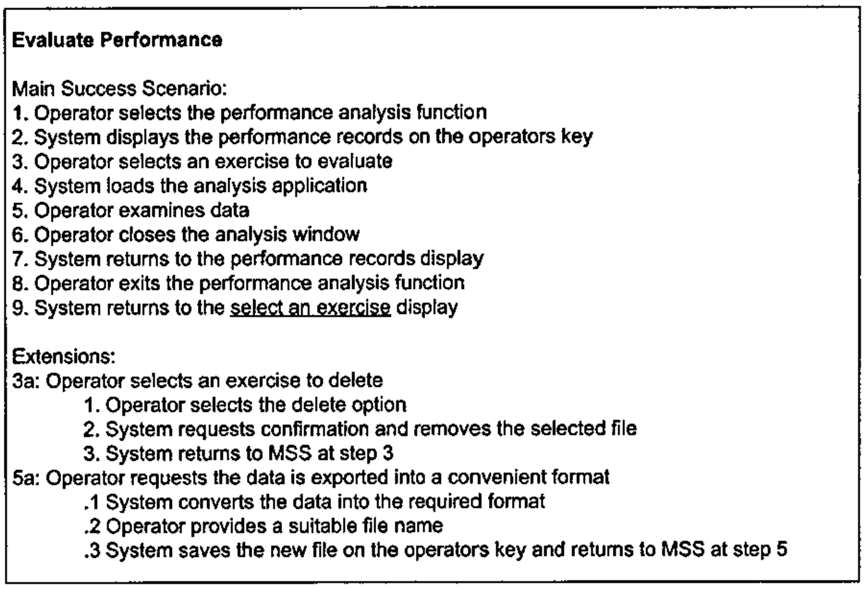
Extensions:
6a: User fails to apply the required force
    .1 System notifies the user that the input force has dropped below the required level
    .2 System stops the exercise
    .3 Operator applies the required force
    .4 System continues the exercise motion and returns to MSS at step 5
6b: User fails to exercise of the required range of motion
    .1 System notifies the user that the correct range of motion has not been achieved
    .2 Operator continues to move the actuator in the incorrect direction
    .3 System records an incomplete move and returns to MSS at step 5
8a: Operator chooses to discard results
    .1 System returns to select an exercise

Figure 6.8: UML use case diagram for the operations and feedback provided during an exercise.

The force applied by the user is constantly monitored and recorded throughout the exercise. If the system detects that the user input has fallen below the minimum threshold level during an active exercise mode, the interface will display an appropriate warning and the motion will be temporarily interrupted. The exercise will recommence as soon as the measured input reaches or exceeds the limiting value. Actuator position is also monitored in parallel with user input. If the user fails to move the actuator over the full range of motion during an isotonic exercise, the system will detected that a partial movement has been conducted and will decrement the repetition count accordingly. A tag will be assigned to the results to identify any incomplete repetitions that were performed during the exercise.

6.2.5 Use case – Evaluate performance

The final use case identified during the development of the exercise system interface was the analysis of performance as shown in Figure 6.9. Exercise data that has been written to the user's storage device can be accessed at any point using the performance analyzer function. The user launches this utility from the exercise selection screen and the system displays the stored performance records. The user can navigate through the data and select an exercise for detailed investigation or permanent deletion. The system will upload this information into a dedicated analysis window which presents the information in a suitable graphical format. The user can assess the results and return to the main list by pressing an appropriate navigation button. An export option was required to convert this information into an alternative format for additional investigation or long term storage.



Evaluate Performance

Main Success Scenario:
1. Operator selects the performance analysis function
2. System displays the performance records on the operators key
3. Operator selects an exercise to evaluate
4. System loads the analysis application
5. Operator examines data
6. Operator closes the analysis window
7. System returns to the performance records display
8. Operator exits the performance analysis function
9. System returns to the select an exercise display

Extensions:
3a: Operator selects an exercise to delete
    1. Operator selects the delete option
    2. System requests confirmation and removes the selected file
    3. System returns to MSS at step 3
5a: Operator requests the data is exported into a convenient format
    .1 System converts the data into the required format
    .2 Operator provides a suitable file name
    .3 System saves the new file on the operators key and returns to MSS at step 5

Figure 6.9: UML use case diagram for the performance evaluation function.

6.3 Exercise system HMI embodiment

Using the information outlined in the product design specification, system behaviour formalised in the UML use case diagrams and knowledge of interface design practices, the process of creating the code for the solution could begin. These documents were used throughout the development process as a reference source for implementing the structure, appearance and function of the program. Coding of the interface was conducted using the Visual Basic.Net programming language (Francesco, 2004) since it was essential that the implementation could be supported and upgraded for future instantiations.

6.3.1 Exercise system HMI structure

The interface was developed, installed and tested on a standard PC unit as shown in Figure 6.10. The basic structure of the software was designed to minimise platform dependency thereby allowing the interface to be transferred to other hardware, such as personal digital assistants (PDA's) and smart phones, without modification or with only minor alterations. The central interface framework is composed of a collection of user controls which have been created to undertake specific aspects of functionality. These controls are initiated by the main framework program and presented in a common position on the system display. Each control will interact with the user and / or undertake background tasks and then close automatically upon completion.

As the user controls are created and removed during normal usage, the interface framework may be required to access the internal database or an external data source. In the instance that a user control requires information specific to the machine, then the framework will provide a link to the database stored on the local host computer to allow the relevant information to be extracted. If the user control requests user specific records or parameters, the framework will connect to an appropriate file system located on a removable storage device. This can be any portable memory device such as a mobile phone, audio player, PDA or flash memory stick. Regardless of the hardware embodiment of this device, the exercise system interface only requires that a basic folder of a known name be created in order to aid automatic detection.

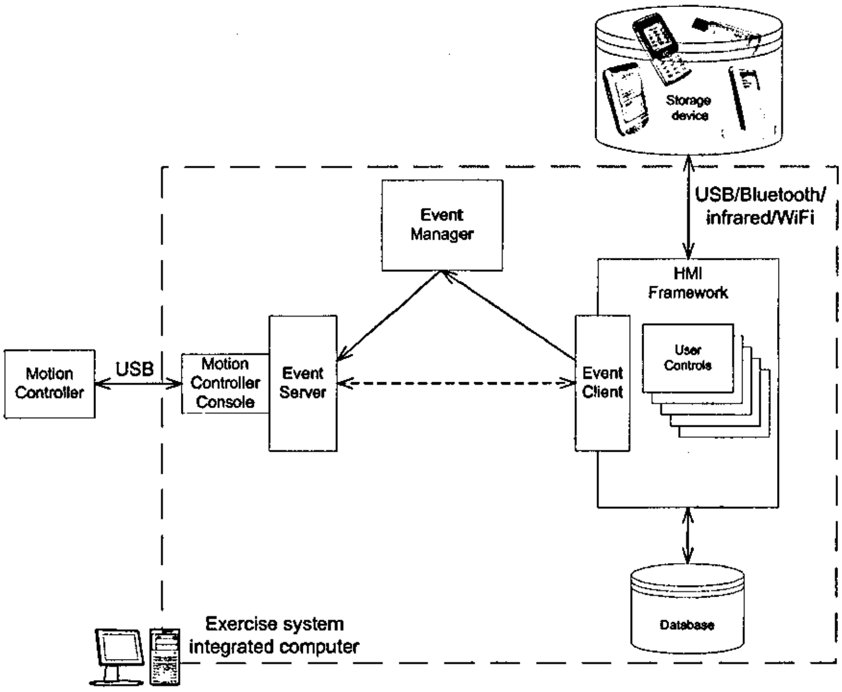


Figure 6.10: Exercise system user interface structure.

In addition to the user based interactions, the interface must also establish communications with the low level control software of the exercise system (see Chapter 5). This connection has been achieved using a scalable module approach. The low level hardware system is connected to the host PC via a USB link which is monitored and accessed by the motion controller console application. This motion controller console provides the basic input / output capabilities to the hardware system. The console application has been developed with an integral "event server" program which communicates with a separate "event client" that is part of the main framework. This connection is not formed directly at start-up but is initially formed using the remote "event manager" application. Assuming no link is present, a request for establishment of communications is sent to the event manager by the event client. The event manager will examine the status of the event server and establish a direct link if ready. This arrangement allows a number of different clients to access a single server or alternatively a single client can communicate with numerous servers. The communications in these multiple node systems are controlled by the event manager which ensures that the correct links are formed or broken at the right time.

6.3.2 System screen segmentation

The user interface developed for the prototype exercise system is based around a standard TFT monitor, keyboard, mouse and PCI card sound system. This interface is positioned close to the main resistance unit to enable the operator to see the on-screen information during normal use. It is envisioned that further developments of the interface will migrate into a single component solution based upon a flat screen TFT monitor with touch screen capabilities and built in audio capabilities.

The interface is designed to provide a number of functions when communicating with the user, which include the presentation and representation of:

(i). Personal information and performance history.
(ii). Operational settings and system state.
(iii). Real time performance measures and exercise feedback.
(iv). Performance feedback and analysis.
(v). Entertainment and e-competition.

A standardised layout has been developed to maintain a consistent style of presentation as the operator navigates through the various operational screens. The fundamental elements of the exercise interface are shown in Figure 6.11. The screen has been divided into four main sections that provide specific functions or feedback. Each section has been designed to display information in a clear and concise manner to ensure there is no ambiguity in the user's interpretation.

Important information and guidance messages for the user are displayed in the panel at the top of the screen. These text based prompts provide the user with instructions and tips for completing tasks or configuring options that are displayed in the main user controls area. Positioned to the right of this panel is a help / information button. If the user requires additional information at any stage during an exercise then this feature can be activated. A detailed explanation of the options, technical terminology and recommended settings are presented in detail in a separate window in the user control area. Once the user is comfortable with the choices that are required, the help window can be closed and the user control will return to the original screen. The status of the Trio connection (see Chapter 5, section 5.1.2) is displayed in the connection status panel. If the connection is lost or the event manager (see section 6.3.1) is unable to establish communications then the interface will instruct the user to check the physical connection and restart the system.

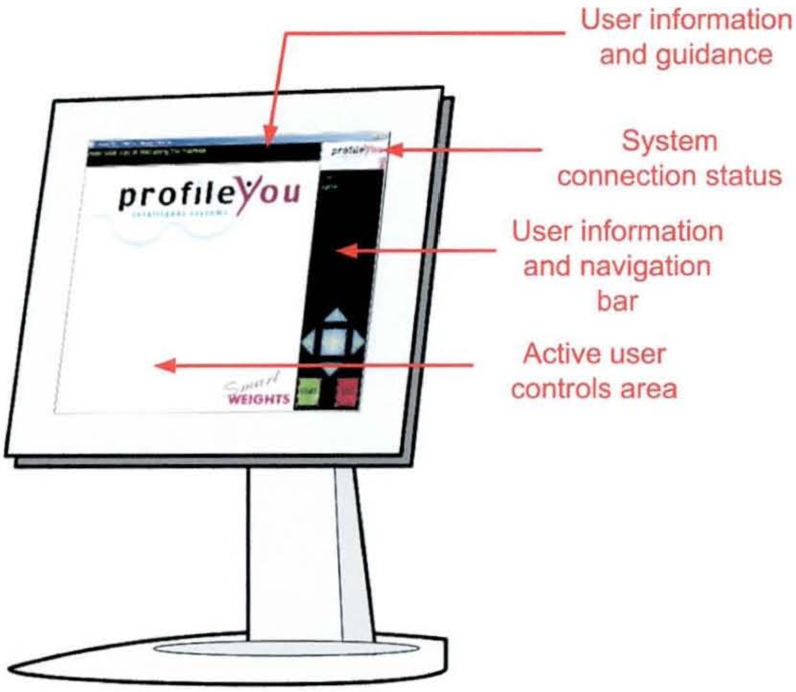


Figure 6.11: Fixed panel structure of the system interface.

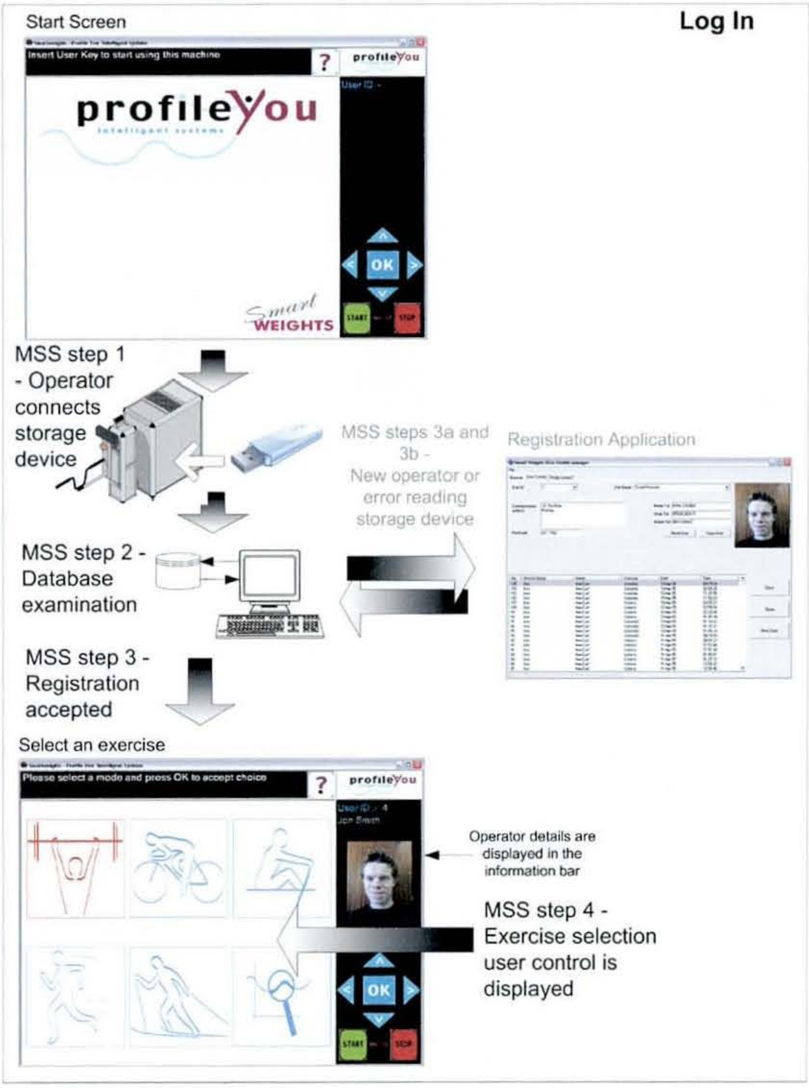
The layout of the panels shown in Figure 6.11 is fixed within the screen display to aid with user exploration and ease of use. The only area which is changed significantly during use is the main user control area. A set of panels have been created using a modular approach which are created and displayed in the control area to guide the user through the process of configuring, completing and analysing an exercise. As each panel is called sequentially, appropriate messages and functional links are established with the surrounding static panels. This panelling technique gives the interface functional modularity such that additional modes and features can be inserted quickly and efficiently without affecting the existing code. Also, as new exercise regimes are developed, adjustments can be made to the original panels to cater for these new practices.

6.3.3 User controls operation and functional flow

The operation of the user control panels was determined by the use case diagrams defined during the initial phases of the interface development (see section 6.2). In order to convert these textual based representations into functional programs, the scenarios that were identified were used as a structure for coding the user controls. The major features and processes that were created using the information from the requirements and behaviour definitions are discussed in the following sections.

6.3.3.1 Interface Log-In procedure

A welcome screen was developed which is displayed upon start up as shown in Figure 6.12. A message in the information panel prompts the operator to connect their storage device (MSS step 1). The system has been configured to inspect automatically external drives for a unique exercise file (MSS step 2). This file system includes the registration information and performance records for the particular user. If this information is acquired, the system will display the user's details and load the exercise selection user control (MSS steps 3 and 4). However, if the operator does not have a pre-registered key, or the data has become corrupt, a separate application was created to manage this information (MSS steps 3a and 3b). This application has been design to run independently and therefore does not require the system to be connected to the exercise device. Using familiar Windows based data entry boxes, tabbed pages and ordered tables; the operator can input their personal details together with information relating to previous performance records and injury history.



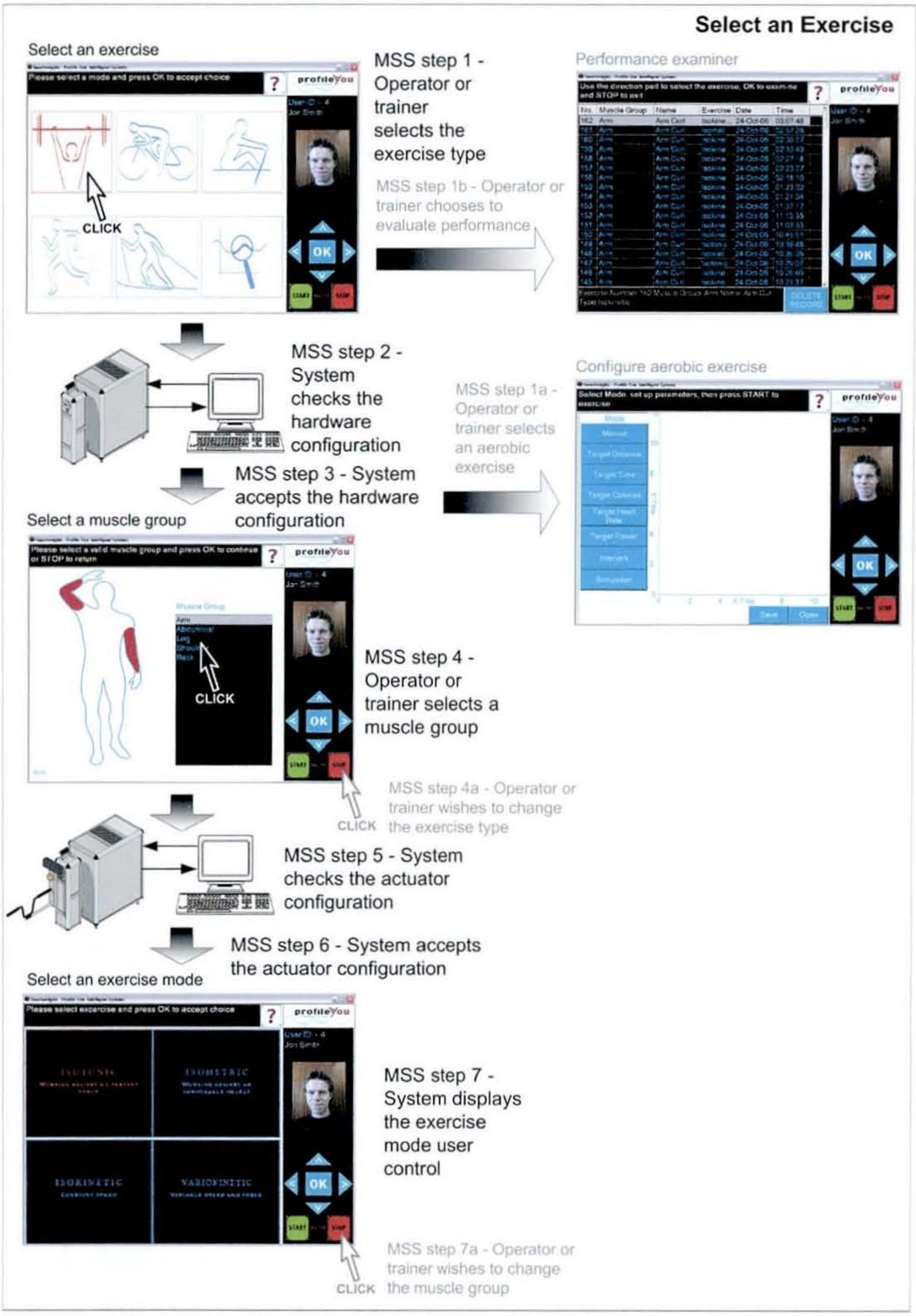
Insert User Key to start using this machine

Please select a mode and press OK to accept choice

Figure 6.12: Screen sequence of the system log in procedure.

6.3.3.2 Select an exercise interface procedure

Once a user has successfully logged into the system, they are presented with a series of metaphoric diagrams to represent the range of exercises that may be selected as shown in Figure 6.13 (MSS step 1). The current exercise selection is identified by a red outline. The user can select an exercise by using the navigation panel and confirm the choice using the OK button. Alternatively, if the system has a mouse or other such device then the user can click anywhere on the relevant image. If the performance examiner icon is selected then the user can review their exercise records as discussed in section 6.3.3.5 (MSS step 1b). If an exercise has been chosen, the system conducts a hardware inspection, as outlined in the UML diagram, to ensure that the secondary positioning system is configured correctly (MSS step 2 and 3).



MSS step 1 - Operator or trainer selects the exercise type

MSS step 1b - Operator or trainer chooses to evaluate performance

MSS step 2 - System checks the hardware configuration

MSS step 1a - Operator or trainer selects an aerobic exercise

MSS step 3 - System accepts the hardware configuration

MSS step 4 - Operator or trainer selects a muscle group

MSS step 4a - Operator or trainer wishes to change the exercise type

MSS step 5 - System checks the actuator configuration

MSS step 6 - System accepts the actuator configuration

MSS step 7 - System displays the exercise mode user control

MSS step 7a - Operator or trainer wishes to change the muscle group

Figure 6.13: Screen sequence for selecting an exercise.

An example interface has been created to demonstrate the functionality of an aerobic user control for the exercise cycle. Selecting a resistance exercise will open a series of sub-options which are discussed in section 6.3.3.3. Assuming the hardware is orientated correctly, the interface displays a basic screen that allows the user to set the fundamental cycling exercise parameters quickly and efficiently (MSS step 1a). If a simple cycling routine is required, then the user can simply set the required resistance level and activate the system without completing complex on screen processes. Real time feedback regarding the distance covered, speed and current resistance level is displayed on the multifunction user control. This particular interface was designed to replicate the configuration and feedback characteristics of current aerobic equipment (see section 6.1.1). These systems require minimal user inputs and provide clear performance monitoring facilities. Ease and speed of setup is essential with such equipment and therefore the aerobic user control was developed to minimise navigation and data entry requirements.

If the user selects the resistance exercise function, the system displays a graphical representation which highlights the core muscle groups that could be exercised using the available hardware components (MSS step 4). A selection can be made by using the navigation panel to scroll through the attached list. If the operator makes an erroneous selection at any point, they can return to the previous user control by pressing the stop button (MSS step 4a). Once a muscle group selection has been made, a second hardware configuration inspection will be conducted to ensure that the secondary positioning mechanism is positioned correctly for the required exercise attachment (MSS steps 5 and 6). If a hardware conflict is identified, the system will automatically reposition the output to a point which corresponds to the exercise selected. When confirmation has been received that the hardware has been configured successfully, the exercise mode user control is displayed (MSS steps 7 and 7a).

6.3.3.3 Configure an exercise interface procedure

The exercise mode user control segments the display to represent the four resistance modes that can be conducted using the system hardware (see Figure 6.14). Basic descriptions of each exercise are provided although the user can access detailed explanations by pressing the help button. Once a selection has been made (MSS step 1), the system analyses the user's storage device (see section 6.2.3) and displays the exercise pre-requisites user control (MSS steps 2, 3 and 4). The range of functions that are activated on the screen is dependent upon the type of information discovered during the analyses of the storage device. If a valid range of motion and one repetition maximum is found then the user control provides full access to the pre-requisite activities. If the user has inadvertently selected an incorrect exercise then they may return to the selection screen at any point by activating the "select new exercise" button (MSS step 5a).

Users with full access may choose to warm up independently although the system has been designed with a dedicated warm up function (MSS step 5b). The aim of this program is to provide a series of low intensity, high volume actions which activate the various physiological and neural systems in a moderate, controlled approach before they are stressed during the main exercises. The warm-up procedure utilises a specific isotonic exercise routine to provide the necessary stimulus. Upon activation, the user interface initiates the isotonic program in the low level software and downloads the specific warm up variable settings. The interface then operates in a standardised exercise feedback state as described in section 6.3.3.4.

Another option provided for users with the correct configuration data is a calibration test (MSS step 5c). This calibration exercise uses the basic functionality of the isokinetic program discussed in section 5.3.7. This procedure is designed to determine the user's current capabilities and performance characteristics. The system prompts the user to complete a series of basic isokinetic tests over a range of different speeds. A full explanation, which is currently textual and graphical although it is envisaged to be video based, is provided at the beginning of the session to ensure the user is familiar with the details of the calibration process.

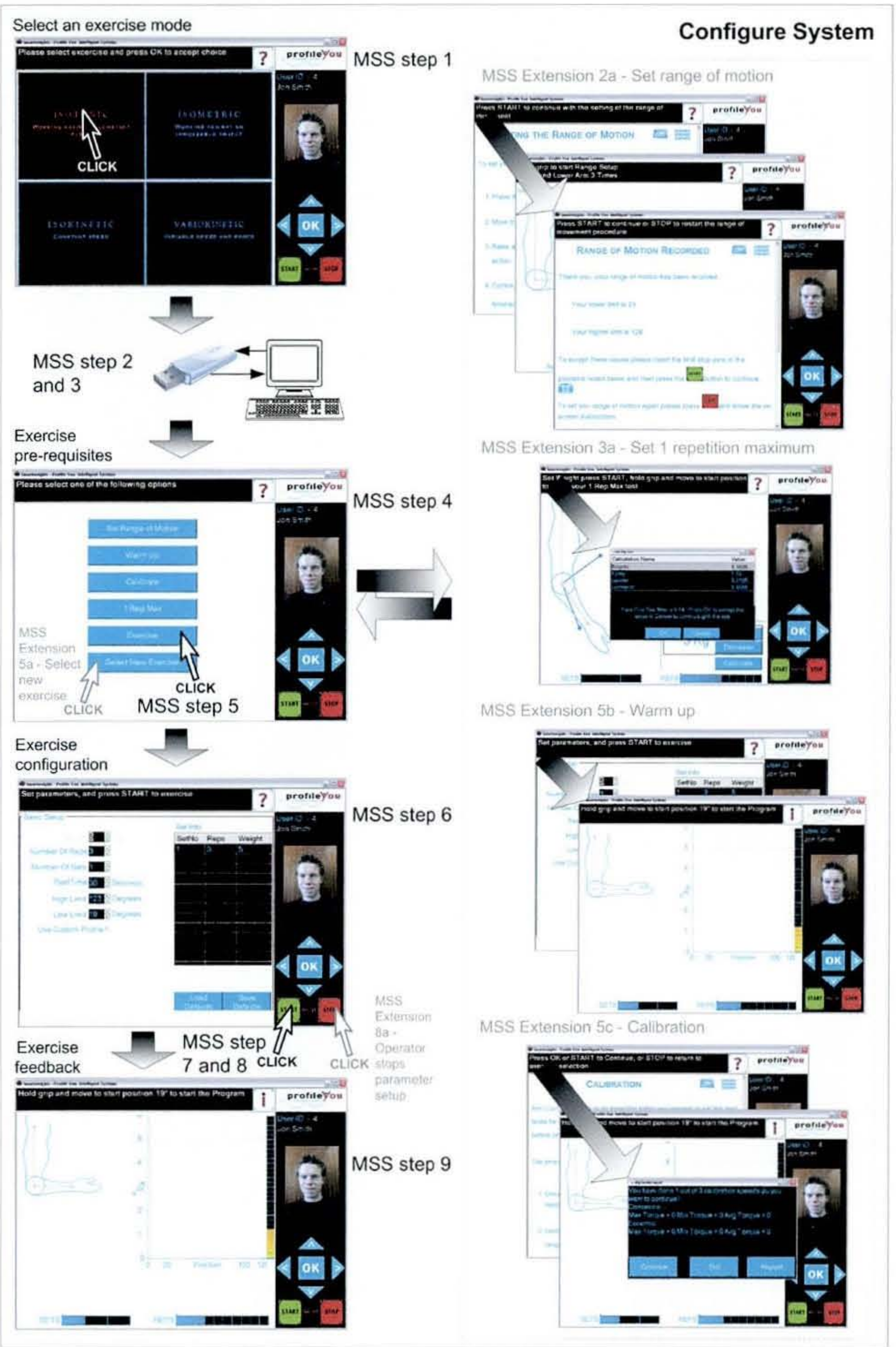


Figure 6.14: Screen sequence for configuring the system for an exercise.

Upon commencement, the system downloads the calibration parameters to the low level software and operates in the standard isokinetic feedback mode (see section 6.3.3.4). The user may choose to skip single repetitions or entire exercise sets, although a minimum of one lift must be completed at the lower speed in order to establish a fundamental working limit. The user is informed of the importance of correct calibration as the information will potentially affect all of the exercises undertaken during that session. The information collected during this phase can be used to set maximum load levels, specify load profiles and identify injury or abnormal activation patterns. Once the test has been completed, a sub-panel is displayed which presents the overall performance figures for the user's information. This sub-panel also features a set of buttons to represent alternative closing actions; continue and save the data, exit without saving or repeat the test. If the user has chosen to repeat the exercise, the system will return to the test setup screen else the pre-requisites options will be redisplayed.

If the user storage device does not contain valid range of motion / one repetition maximum data or the information has expired, the system will restrict the pre-requisite options such that the appropriate test must be conducted. The range of motion information is used to prevent the user from exceeding their current capability and acts as a set of virtual e-stops which are used in subsequent programs. Once the "set range of motion" option has been selected (MSS step 2a), the user is given instructions to complete three basic lifting motions over the widest range of movement that they can achieve. The program monitors the position of the actuator and performs a series of comparisons in order to determine the maximum and minimum positions achieved. The limits of motion for each repetition are stored and an average calculated to determine the overall operational range.

In order to prevent the recording of erroneous or non-representative values, a positional threshold has been specified which requires the three data points to be within a predefined boundary before the final value is calculated. Once the upper and lower limits have been calculated, they are displayed and must be accepted by the user before they are downloaded to the storage device. In the instance that a problem was encountered during the test, the user may choose to repeat the process without saving the data by pressing the stop button in the navigation panel.

As discussed in the literature review (see Chapter 1), the one repetition maximum test procedure is an established method for provided a quantitative assessment of an individuals performance. This procedure involves an iterative isotonic lifting regime which is designed to estimate the maximum load that the person can lift only once using correct form and without assistance. In general, only experienced exercise professionals will actual conduct a single lift at the maximum weight as this can cause serve injury if correct precautions are not taken. It is much more common to conduct a high number of repetitions at a lower weight. The total number of complete lifts and the associated weight can then be entered into a specific algorithm to calculate the theoretical one repetition maximum. The accuracy of this prediction will depend upon the number of repetitions that are completed and the precise calculation that is employed.

The test procedure has been created as a set of specialist operational parameters of the basic isotonic low level program (MSS step 2b). The user is prompted to estimate an initial starting weight or use the guide value calculated from the calibration results. Once this has been set, the program operates in precisely the same way as that described in section 5.3.8. The user must lift the weight over the full range of motion for a given number of repetitions. If this set of exercises is completed successfully, then the weight can be increased incrementally and the process repeated until the user can not complete all of the required repetitions.

Once this failure set has been determined, the precise number of repetitions and the final weight is recorded and entered into one of the four predictive equations that have been identified. The Brzycki, Epley and Lander (Brzycki, 1993; Epley, 1985; Lander, 1985) equations allow the predicted one repetition maximum, 1RM, to be calculated from the sub-maximal weight selected, W, and the number of repetitions completed, n.

$$\text{Brzycki 1 RM} = \frac{W}{1.0278 - 0.0278n} \tag{6.1}$$

$$\text{Epley 1 RM} = (W \times (0.0333 \times n)) + W \tag{6.2}$$

$$\text{Lander 1 RM} = \frac{W}{1.013 - 0.0267123n} \tag{6.3}$$

If the user is consistent in selecting the same formula after every test, this information can be used to monitor the improvement in user performance over time as they adapt to the applied training stimulus. The calculated value is also stored as a key operational parameter on the user's storage device. This theoretical weight is used to define the maximum load value that can be selected in a basic isotonic exercise program. Experienced users may increase this value in order to conduct eccentric exercises although the range is still limited to 150 percent of the one repetition maximum (based on Hortobagyi & Katch, 1990). Once the user is satisfied with the predicted one repetition maximum then the information can be stored and the program exited. Alternatively, the user may choose to continue the exercise by cancelling the exit command thereby returning the system to the initial starting state.

Assuming the user has completed the range of motion and one repetition maximum protocols, the interface will permit access to the main exercise configuration screen (MSS step 5). This user control is an input focused interface where the primary training parameters can be defined (MSS step 6). Where practical, a common data entry style has been maintained between each exercise mode. Parameter inputs are generally made using the embedded numerical controls and table structures which can be adjusted using the navigation panel or interface input device. Depending upon the complexity of the information, interactive graphs and graphics have also been developed to improve the ease of setup. A detailed explanation of each of the configuration processes is provided and can be accessed by the interface help button.

A set of default parameters are loaded automatically when the user accesses the configuration interface. These values represent the archetypal training routines identified during the literature review and are combined with user performance data to create a configuration file which allows the user to begin exercising immediately. If the user wishes to make alterations to these values in order to create a customised exercise, these changes can be saved to the storage device as additional defaults which can be recalled at any time. Once the necessary settings have been defined, the user can confirm the values and begin the exercise by pressing the start button (MSS steps 7 and 8). The relevant variables and values are downloaded to the low level software and the interface displays the exercise feedback user control (MSS step 9).

6.3.3.4 Exercise feedback interface

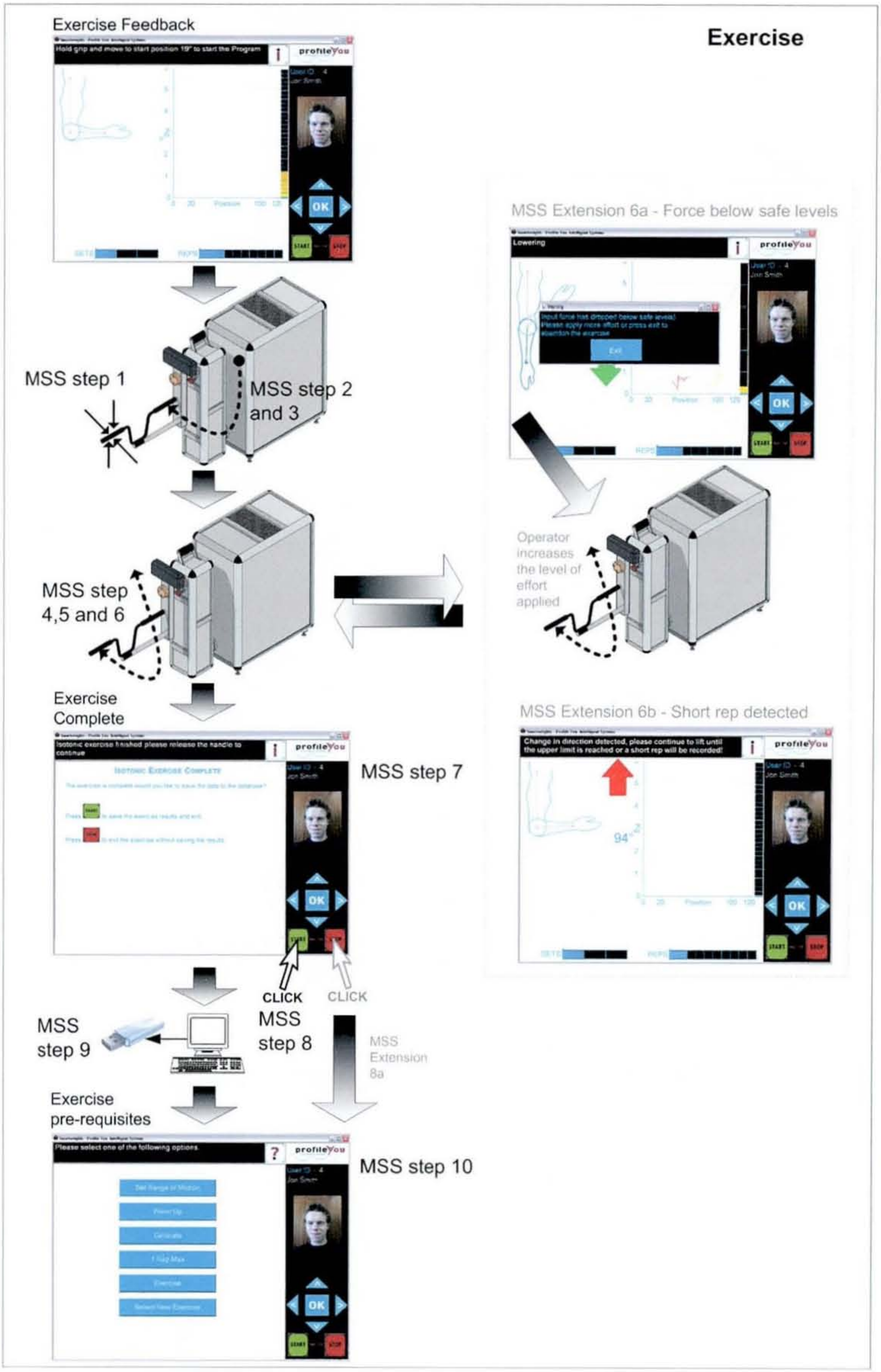
In order to begin the exercise, the user must apply pressure to the attachment sensor (MSS step 1). Once the threshold level has been exceeded, the interface will indicate the start position for the actuator and the user will be instructed to rotate the mechanism to match the graphical representation (MSS step 2). During this positioning phase, the system remains inactive until such a time that the position acquired is within a threshold value of the demand location. The user is informed by the interface that the required proximity has been achieved and the system will automatically drive the attachment to the precise start position as shown in Figure 6.15 (MSS step 3).

Once in position, the system will either provide a count down to the beginning of the exercise or wait until the user provides a threshold input force, depending upon the particular exercise selected (MSS step 4). The interface provides a visual representation of the position of the limb system being exercised and the target position for each motion. As the various raising and lowering movements are completed (MSS step 5), the remaining sets and repetitions are displayed and decremented automatically on the screen. A simple graphical representation of the user's force production is provided in real time.

The interface monitors the force applied by the user throughout the period of the exercise as discussed in section 6.2.4. Depending upon the exercise mode, a minimum input threshold will be determined to ensure that the user is training efficiently under nominal conditions. If the force falls below this threshold level then the system will encourage the user to increase their effort before implementing a controlled emergency stop procedure (MSS step 6a). A sub-panel is displayed which informs the user that the applied force was insufficient and the repetition must be repeated. Monitoring the force in this manner ensures that abnormal variations in force due to injury or other impairment are detected and loading reduced before further damage is incurred.

A simple arrow graphic is used to represent the direction of motion of the actuator. During an isotonic exercise, if the user fails to reach their predefined range of motion before changing the direction of motion, then the arrow colour will alter to indicate that a short repetition has been detected (MSS step 6b). The information panel warns the user that they have not achieved the required limit and requests that they continue in the previous direction. If these warnings are disregarded, the interface will allow the user to continue to move in the incorrect direction until a threshold is exceeded. At this point, a short rep is recorded in the data, the interface decrements the rep count and immediately proceeds with the next motion in the set.

If the required number of repetitions and sets are completed successfully, the interface will prompt the user to save the performance data or alternatively discard the information before exiting (MSS step 7). Records to be saved are downloaded to the user's storage device and the interface returns to the exercise pre-requisites user control (MSS steps 8 and 9). If the user decides that they are unable to finish a particular exercise before completing the designated number of repetitions then they may activate the stop button on the user interface at any time or reduce the pressure on the grip sensor. This will stop the training program's current operation and clears the remaining repetitions. The user may re-activate the system and start the next set of exercises or, if they no longer wish to proceed with the current training routine, they may skip forward any outstanding sets and exit the exercise (MSS step 10).



Hold grip and move to start position 19° to start the Program

Lowering

Input force has dropped below safe levels! Please apply more effort or press exit to abandon the exercise

Change in direction detected, please continue to lift until the upper limit is reached or a short rep will be recorded!

Isotonic exercise finished please release the handle to continue

Isotonic Exercise Complete

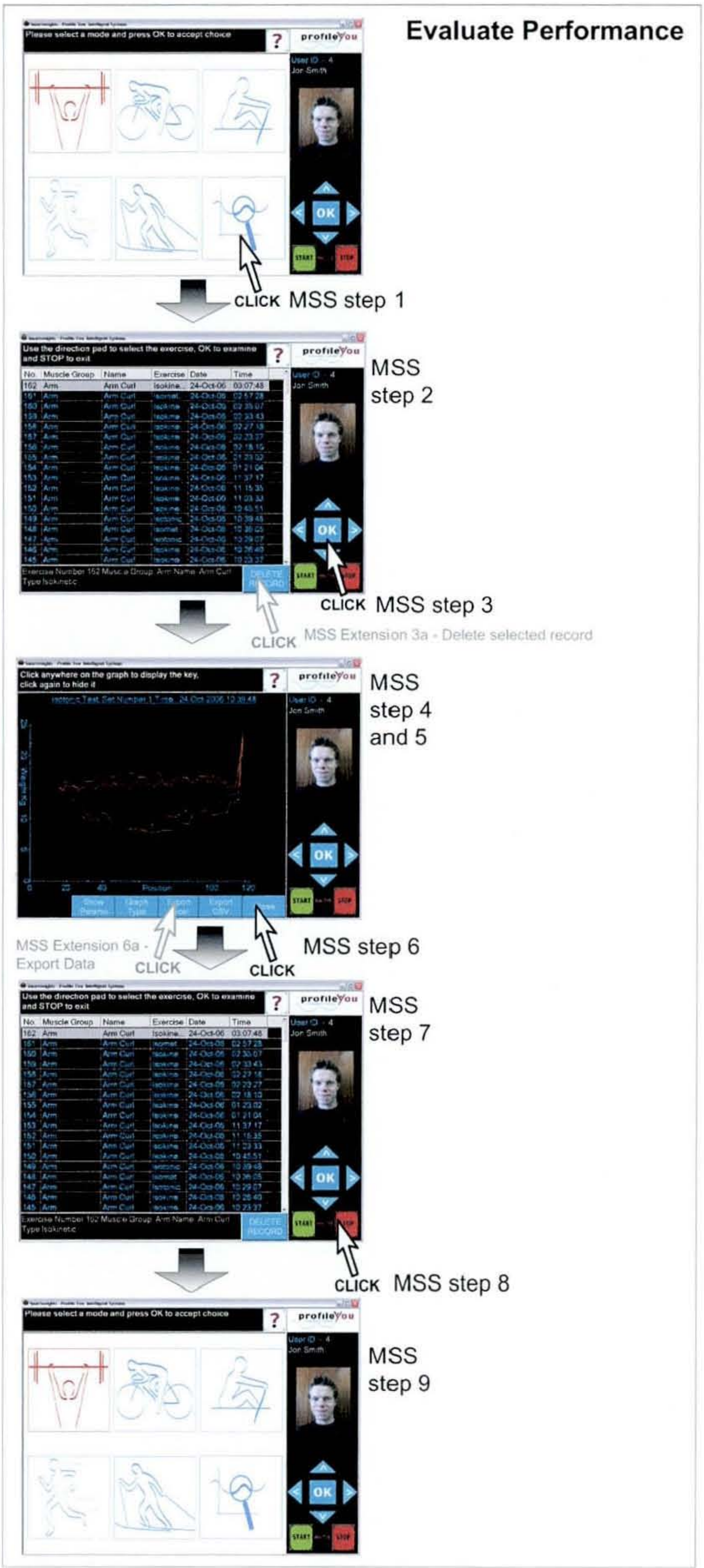
Please select one of the following options.

Figure 6.15: Screen sequence for conducting an exercise.

6.3.3.5 Performance monitor interface

Once an exercise has been completed successfully and the data downloaded to the user's storage device, this information can be accessed using the performance examiner function (Figure 6.16). The user must navigate from whatever interface they currently have displayed until they reacquire the exercise selection screen. The performance examiner user control can be initiated by selecting the appropriate graphic in the selection grid (MSS step 1). The interface examines the user's storage device for associated files and displays these records in a simple tabular format (MSS step 2). The user can scroll through the list using the navigation panel and select a specific exercise to view by pressing the "OK" button (MSS step 3). Additional details relating to each file and the information contain there in are displayed in a preview window at the bottom of the user control area. The user may choose to delete a record from the list, and thereby permanently remove it from their storage device, using the "delete record" button (MSS step 3a).

If the user has chosen to explore a particular exercise, the interface uploads the relevant information into a graphing utility which presents the performance data in a familiar format (MSS step 4) in Figure 6.16. The data for each repetition within a set is overlaid on the graphing area and differentiated by the colour of the line. A set of additional feature buttons have been created below the graph area to provide the user with the necessary analysis functions without having to navigate to a dedicated options page. System configuration details relating to the on-screen data can be accessed by pressing the "show params" button. In order to improve the usability of the system results, a number of export functions have been included to convert the files into more commonly used formats (MSS step 6a). Once the user has finished their analysis, the graphical display can be closed (MSS step 6) and the performance table can be exited by pressing the stop button in the navigation panel (MSS step 8).



Please select a mode and press OK to accept choice

Use the direction pad to select the exercise, OK to examine and STOP to exit

Click anywhere on the graph to display the key, click again to hide it

Use the direction pad to select the exercise, OK to examine and STOP to exit

Please select a mode and press OK to accept choice

Figure 6.16: Screen sequence for analysing performance post-exercise.

6.3.4. Interface reconfiguration and customisation.

The screen captures shown in section 6.3.3 represent the nominal interface style which was developed for functional testing purposes. Although the software structure is relatively fixed, the presentation of the information embedded in this code exhibits a high level of flexibility. The interface appearance was designed with a bold colour scheme and simple, easy to read text supplemented by clear diagrams / illustrations. This approach has been adopted to ensure the user is able to understand and react to the information being presented during periods of prolonged physical exertion or short maximal efforts.

In order to demonstrate the level of customisation that is achievable with the exercise interface platform, an array of configuration options have been incorporated into the software. Figure 6.17 identifies the display elements which can be altered on the current interface which include the following:

(i). Font, size and colour of the text displayed in the instructions in panel.
(ii). Font and colour of the text in the user control panels.
(iii). Graphical representation of the remaining reps and sets.
(iv). Relative force display.
(v). Background image of the user control panels.

The configuration files which contain information regarding the desired appearance are located on the user's storage device and uploaded during the log-in procedure. The interface adjustments are made automatically in order to avoid lengthy and complicated set-up routines which can occur when providing customisable features. Providing the user with reconfiguration facilities such as these increases system interaction and enhances usability.

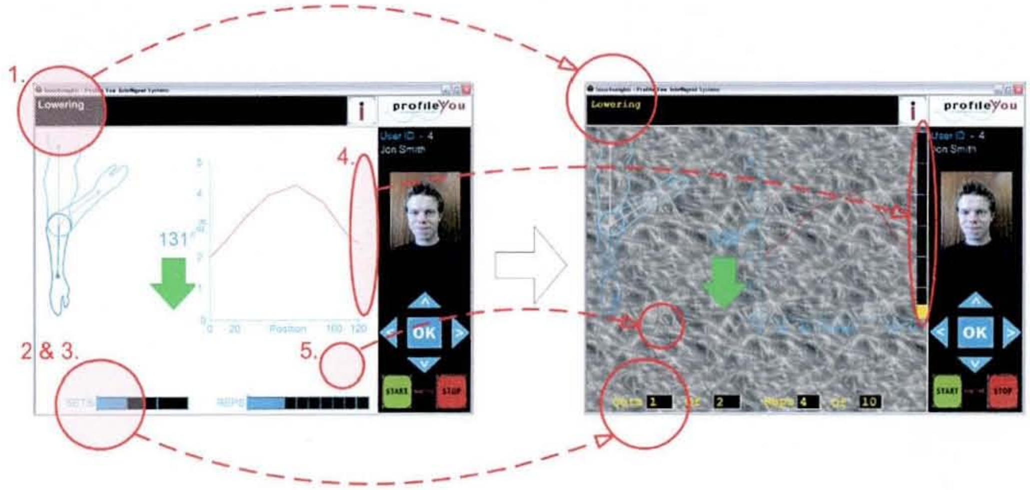


Figure 6.17: Illustrated example of the interface reconfiguration capabilities.

6.4 Summary

The PC based software interface was developed to provide a simple, convenient and quick method for operating the low level control programs and hardware components of the integrated exercise system. Information from the product design specification and CIMOSA diagrams was converted into a formal behaviour structure using the UML use case modelling language. These diagrams were used in conjunction with user interface design literature to create the experimental application successfully and efficiently.

The distributed communication strategy which manages the connection between the interface and the machine control software has proved to be a robust connection during testing and development. The fixed framework structure of information and input panels on the interface introduced a level of consistency to the navigation functions and basic operations. Using this approach, the system can be scaled and reconfigured to accommodate additional functions by introducing new user controls without having to produce entire screens and interconnections. The system provides active guidance for the user through the information panel and help button. The occurrence of erroneous selections is reduced by restricting access to the on-screen options where relevant. If an option is selected mistakenly, the ability to return to the previous screen using the navigation button should improve discoverability

(Spolsky, 2001) of the interface as the implication of such choices are dramatically reduced. In order to develop a fully implemented solution, detailed usability experiments are required to quantitatively assess the function of the interface and identify elements for improvement.

The current interface appearance is relatively functional although some customisation capabilities were incorporated to illustrate the program versatility. It is envisioned that future developments would enhance the style and aesthetic presentation of the interface. The inclusion of additional entertainment / multi-media user controls which provide full audio and video playback capabilities for music, telephone conversations, e-competition and gaming would allow additional research to be conducted into exercise motivation using a fully integrated system. Distribution and interlinking of these interface and exercise devices for the purpose of networked performance monitoring and injury prevention should also receive further work as this is currently an area of intense investigation. In order to move towards a universal exercise database the initial results or data export functions must be made compatible with the main commercial systems currently available.

Chapter 7

Validation and reliability testing

7.0 Introduction

A multi-component assembly such as the modular exercise system developed during this research relies upon the precise connection and interaction of individual sub-systems to create a fully integrated solution. In this application, analogue measurement devices convert physical motion into electrical signals for software control and data recording. Each of these devices has individual operational characteristics and accuracy levels. The combination of these variances and mechanical tolerances will introduce uncertainty in the magnitude of the system inputs and outputs. Therefore, in order to quantify the effects of these inaccuracies it is important to analyse the performance of the complete machine.

There are two main attributes which must be investigated to determine the operational capabilities and data collection facilities of a system. The information and actions of the machine must be validated to ensure that the recorded output is representative of the demand input and these functions must also be shown to be consistent and repeatable. When measuring human performance it is essential that the results produced are valid to permit machine comparisons. Verification is required to ensure that improvements recorded during training are not due to alterations in the intrinsic machine errors.

The experimental routines that were selected for analysing the modular exercise system are illustrated in Figure 7.1. Initial testing was conducted using calibrated loading and recording equipment in order to provided a reliable machine assessment. The key parameters of each exercise mode were identified and tested independently. Once the validity and reliability of the system was determined, a series of user based experiments were also conducted to enable the results to be compared with alternative exercise machines reported in the literature.

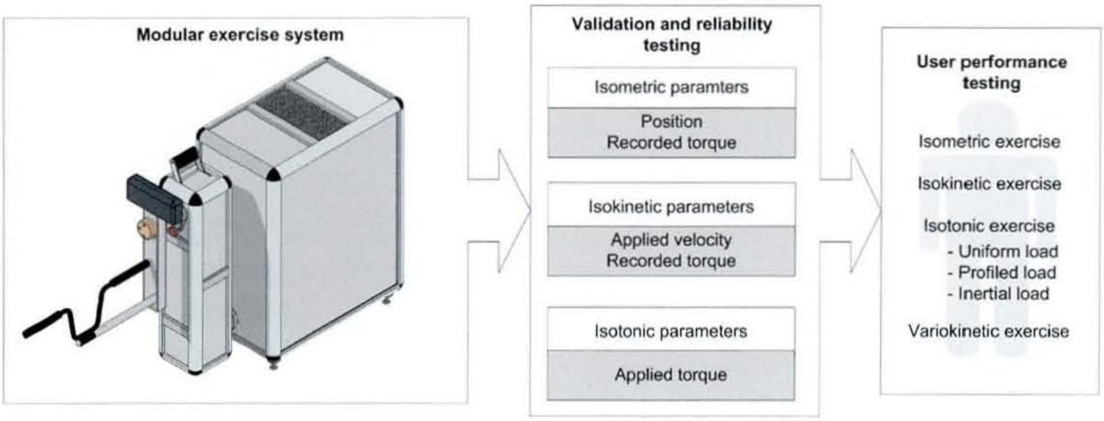


Figure 7.1: Experimental routines selected to analyse the operation and data collection facilities of the modular exercise system.

7.1 Experimental methodologies

Multiple experimental tests were developed to assess the mechanical and electromechanical validity and reliability of the modular exercise system. These tests were designed to monitor the key variables of each exercise mode independently and have been categorised accordingly. The magnitude of each variable was examined over a range of operating conditions to ensure that performance was consistent in all scenarios. The validity of the system variables were proven by comparing the resulting outputs to those recorded using external and independent measurement devices.

7.1.1 Isometric

Test position and recorded torque are the fundamental variables of an isometric exercise. During these experiments, the modular exercise system software was configured to run the isometric exercise protocol. For positional assessment, the secondary positioning system was orientated vertically and the arm curl exercise attachment was connected. A common reference position was determined by positioning the arm curl attachment vertically upright using a Solatronic EN17 hand held digital inclinometer. Once this state had been acquired a datum routine was initiated to reset the software position monitoring system to zero.

Demand position, D_{pos}, was achieved by manually positioning the arm curl attachment over a total range of 180 degrees in 10 degree increments as shown in Figure 7.2. The system was moved between points in a random manner to simulate normal operating conditions. Once the proximity of the attachment to the test location was within tolerance range, the system was activated and accurate adjustment was conducted automatically by the machine. A predetermined 15 second wait was undertaken at each incremental step. During this period the machine would hold position and allow the actual angular displacement, A_{pos}, to be measured using the inclinometer. The location of the inclinometer in relation to the exercise arm was fixed throughout the testing procedure. Each angular increment was tested a total of five times at different intervals.

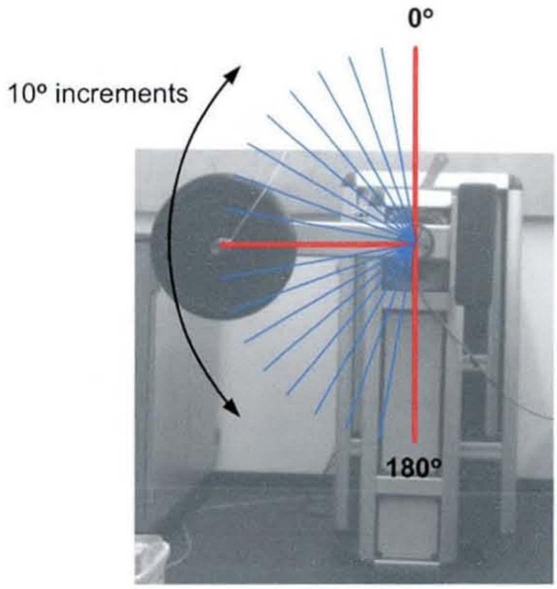


Figure 7.2: Isometric torque measurement test positions.

Isometric torque assessment was conducted to determine the static toque measurement capabilities of the modular exercise system. A vertical datum position was established for the arm curl attachment before each test using an identical procedure to that used during the positional experiments. A series of isometric tests were conducted at 45 degree intervals over a range of 0-180 degrees. At each of these test locations 5, 10, and 15kg weights were applied at a known distance along the arm curl attachment. Standard cast iron weight plates were used to load the system which equate to the respective load intervals. Due to relatively wide manufacturing tolerances, the actual combined mass of the plates is shown in Table 7.1. The voltage output from the torque transducer was passed through the motion controller's analogue-to-digital converter and the resultant value, τ_{out}, was recorded. This output was monitored for a period of 5 seconds at a sample rate of 10Hz to identify possible signal drift.

Demand Weight (kg)	Actual Weight (kg)
5	4.949 ± 0.001
10	9.972 ± 0.001
15	14.921 ± 0.001

Table 7.1: Measured mass of the incremental plates used to load the arm curl attachment.

The output torque was compared to the theoretical torque, τ_{calc}, which was calculated using knowledge of the length, L_{arm}, and the relative angle, θ_{arm}, of the arm curl attachment as shown in Figure 7.3. Each load and position combination was repeated during five separate tests in order to asses the reliability of the data produced.

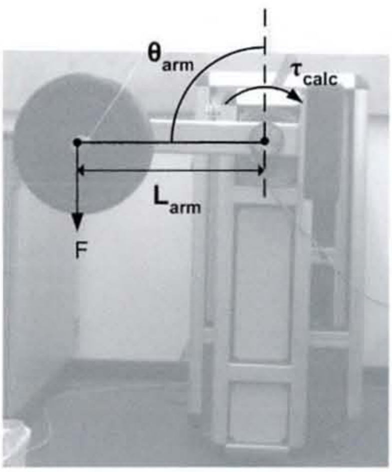


Figure 7.3: Isometric mechanical loading arrangement for calculating the resultant torque.

7.1.2 Isokinetic

The fundamental parameters of an isokinetic exercise are drive velocity and applied torque. The modular exercise system software was configured to run a standard isokinetic test at the predefined velocities over an angular displacement of 180 degrees from a vertical datum set using the hand held inclinometer. A range of speeds: 50, 100, 150, 200, 250$^{\circ}s^{-1}$ were utilised to represent those used in practical isokinetic performance analysis tests in both concentric and eccentric directions of motion. For each set of experimental velocities, V_{in}, the arm curl attachment was tested in an unloaded and loaded state. In the loaded condition, a set if weight plates with a combined mass of 19.62kg, were placed on the attachment at the conventional point of contact.

To evaluate the validity of the velocity control of the modular exercise system a vision based analysis technique was employed. A Photron Fastcam APX RS Mono high speed video camera was positioned in parallel with the rotational movement plane of the arm curl attachment. The output from the camera was digitised and stored on a standard PC using the Photron Fastcam Viewer software Version 2.4.3.8. A manual trigger was used to activate the recoding procedure which was set to capture images at a rate of 500fps. The image sequences were processed using a separate PC based analysis program, Media Cybernetics Image Pro Plus 5.0.

During an isokinetic move there are three distinct phases: acceleration, constant velocity and deceleration. In order to assess the velocity performance of the modular exercise machine, the average speed during the constant velocity phase was analysed. Using the Image Pro Plus software, the time taken for the arm curl attachment to move an angular displacement of 120 degrees starting from a point 30 degrees from the datum location was recorded. This area of interest (AOI) is shown in Figure 7.4. The time period was used to determine the average speed, V_{avg}, over the experimental displacement.

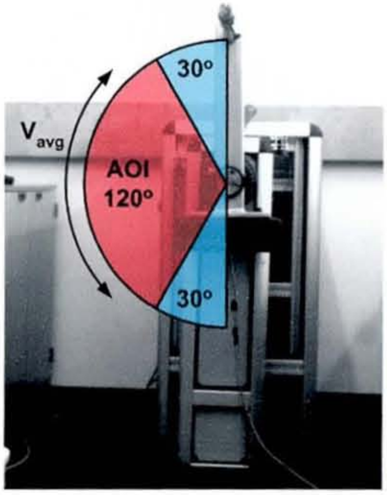


Figure 7.4: Area of interest used to determine average velocity achieved during isokinetic testing.

This angular displacement area of interest was also used to monitor the dynamic torque measurement facilities of the modular exercise system. This window was used to remove the inertial loading effects experienced during the acceleration and deceleration phases of the movement. Three different loads (5, 10 and15 kg) were applied at a known distance along the arm curl actuator. The software system was instructed to complete one isokinetic repetition consisting of a single concentric and eccentric motion at a nominal speed of 50 degrees per second. The output of the torque transducer during the test period was recorded at a rate of 10 Hz. Each test was repeated independently a total of five times to evaluate the repeatability of the results recorded.

The observed analogue values were converted into equivalent torque measures, τ_{out}, and compared to the theoretical torque, τ_{calc}, that would be expected from the mechanical arrangement of the system. The validity of the output would be demonstrated by the level of correlation between the theoretical calculations and the adjusted measures.

7.1.3 Isotonic

During an isotonic exercise the modular exercise machine operates in a torque control mode to apply a fixed or variable force against the action of the user regardless of the input. In order to investigate this dynamic force production feature, the software was configured for a standard isotonic routine. The arm curl attachment was lowered to a position 90 degrees to the vertical, using the hand held inclinometer to verify the location acquired. A fixed surface was brought into contact with the arm curl attachment from below thereby preventing any movement of the system. The experimental "virtual" weight, W_{in}, was entered into the software configuration file and the exercise was initiated. Given the physical arrangement of the mechanical apparatus, the torque produced by the system, τ_{in}, would produce a force, F_w, perpendicular to the orientation of the arm curl attachment which would be applied directly to the fixed surface as shown in Figure 7.5.

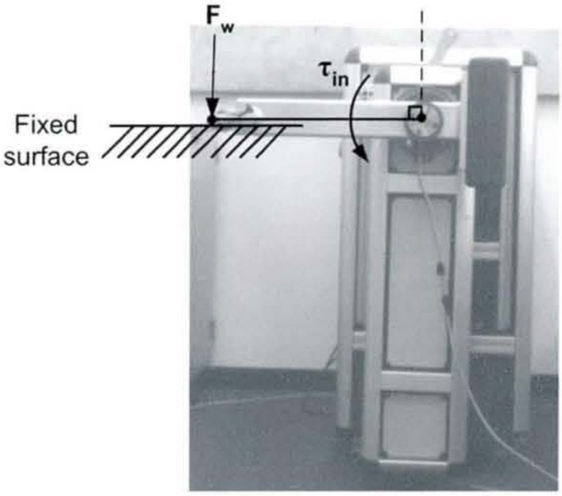


Figure 7.5: Equipment configuration for isotonic weight simulation tests.

Although angular motion was restricted, the resistance elements should continue to apply the required torque, as requested by the software, in this stationary condition. The analogue output of the torque transducer during the test period is processed by the motion controller to represent the torque applied by the system, τ_{out}. This analytical figure can be compared to the demand output in order to examine the validity of the isotonic loading facility. Five separate isotonic routines were conducted to ensure that a reliable result was achieved. The output of the torque transducer was monitored every five seconds for a total period of sixty seconds in order to identify any time related drift in the applied force.

7.1.4 Statistical analysis

Statistical analysis was performed on both the validation and reliability data. The validity of the modular exercise system was assessed by comparing each of the measured variables to the demand input using coefficients of determination, R^2, in order to identify the magnitude of variability in the data. The mean error, M_{error}, between these recoded values and the standard error of the mean, SE, in the data was also calculated. Reliability of the measurements was evaluated using the standard deviation, SD, of the collective data and the coefficient of variation, CV, to provide a relative measurement of distribution.

7.1.5 User performance analysis

Preliminary user performance analysis experiments were conducted to assess the congruity of the data recorded using the modular exercise system against documented test results and reference measures. A single healthy male subject aged 26 with no previous injuries or upper body impairments was used during the exercise routines. The subject, who was familiar with the individual exercise modes, was allowed to warm up prior to each training session. These sessions were conducted on separate, non-consecutive days to avoid fatigue induced performance anomalies.

The isometric tests evaluated the strength of the user through a simple arm curl operation during which the user provided a force against the actuator using both arms in a bilateral contraction. Five test positions where selected and evenly distributed over the users range of motion, which was determined using the modular exercise system range of motion protocol (see Chapter 5, section 5.3.3), from 0 (point of maximum extension) to 137 degrees (point of maximum contraction). At each test position, the user exerted the maximum force possible against the stationary actuator for a period of 3 seconds (Atha, 1981). This duration was selected to ensure that a maximal contraction was achieved. Three tests were conducted at each position with individual tests separated by a two minute rest period.

For these experiments, the system was configured to complete a series of three maximal isokinetic bilateral arm curl exercises over the user's full range of motion at a constant velocity of 50 degrees per second. Both concentric and eccentric contractions were completed with no rest period between the repetitions. The results have been screened to remove the inertial effects of the system acceleration and deceleration. Therefore, the area of interest was reduced to an angular displacement of 77 degrees from 30 degrees to 107 degrees.

The operational requirements of the isotonic program are to provide the user with a constant load against which to exercise thereby simulating a standard set of free weights. The first set of tests was conducted using a "virtual" weight of 10kg without inertial loading. The second series of exercises were completed with a customised load profile (e.g. see Figure 7.6) whilst the third set of trials was conducted with a "virtual" weight of 10 kg and inertial effects activated. The user was instructed to complete five repetitions over their full range of motion against the specified resistance.

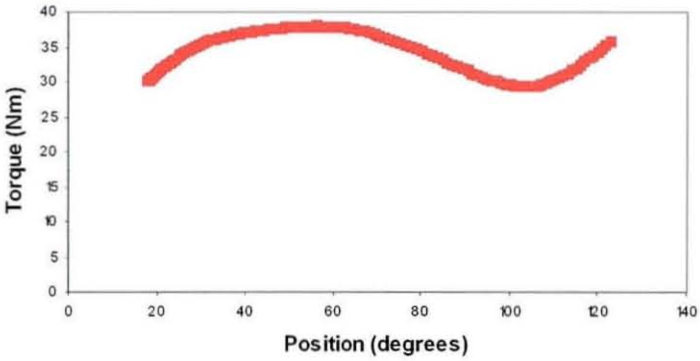


Figure 7.6: Isotonic customised load profile for user testing.

An example variokinetic exercise was devised to demonstrate the operational principles of this novel training mode. Simple velocity and torque profiles (see Figure 7.7) were created and entered into the software reference tables. The user was instructed to complete three independent concentric exercises. During each repetition the user was made aware that they should attempt to move the arm curl attachment at the velocity as indicated on the display of the modular exercise system.

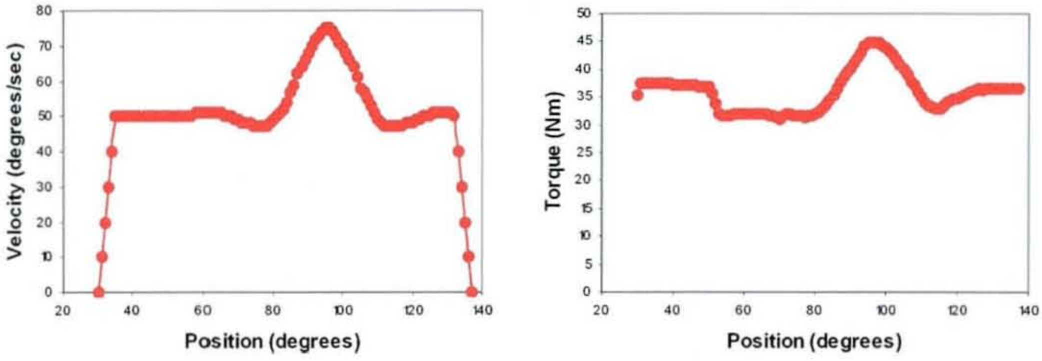


Figure 7.7: Variokinetic velocity and torque profiles for user testing.

7.2 Results

The following data is a summary of the results collected during the validation and reliability tests designed to calibrate the system and confirm the accuracy of operational code. All tests were conducted with the same arm curl attachment which was connected to the modular exercise system via a central shaft as discussed in Chapter 4, section 4.5. Although this actuator featured a fixed counter weight, it became apparent during initial testing that the system was not perfectly balanced and therefore an additional torque component was being introduced into the measurement data. In order to remove this discrepancy a series of un-weighted isometric and isokinetic tests were conducted to determine the torque versus position characteristics of the attachment mechanism.

7.2.1 Gravity correction

A set of calibration tests where conducted to determine the magnitude of gravity correction for the chosen actuator. The first series of tests where designed to examine the static measurement offset during isometric exercise. The system was configured for a standard isometric exercise and the resultant torque was recorded over a range of 180 degrees at ten degree intervals. Position zero represented the vertically upward position and was verified using the hand held inclinometer. Five tests where conducted at each load / position combination and the torque output data for each trial was recorded for a period of five seconds to prevent erroneous results from signal drift.

The second series of gravitational experiments were conducted using a basic isokinetic test. During these tests the system was programmed to conduct a simple isokinetic repetition from zero to 180 degrees and back to zero at a constant velocity of 50 degrees per second. The output of the torque transducer was recorded throughout this motion and the test was repeated on five separate occasions. The torque data was windowed between 30 and 150 degrees to exclude those values measured during the acceleration and deceleration phases of the movement which would include inertial effects. The results of these gravity correction tests are shown in Figure 7.8. Both the isometric and isokinetic data demonstrated a sinusoidal relationship that would be expected when rotating an out of balance mass about a central pivot point.

The values recorded during the separate tests correspond closely with a coefficient of determination of $R^2=0.9906$. This suggests that the sinusoidal trend line in Figure 7.8 could be used to correct the data recorded during use to provide a realistic representation of the torque produced. This relationship was translated into an embedded algorithm for automatic torque correction of validation and reliability test data and amendment of user performance figures. In order to determine the actual torque, τ_{act}, from the measured data, τ_{out}, the following expression can be used assuming that the corresponding angle of the actuator, θ_{arm}, is know for each measurement.

$$\tau_{act} = \tau_{out} \times \left(Sin\theta_{arm} \times 15.22\right) \tag{7.1}$$

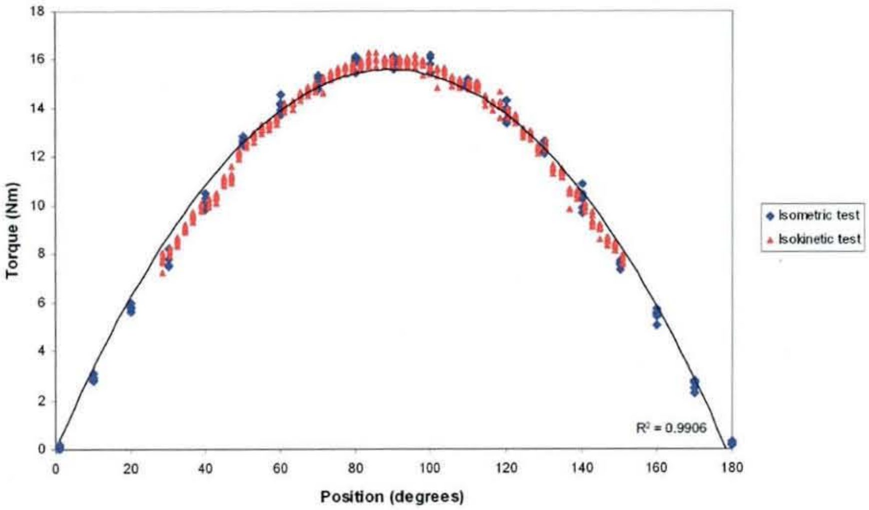


Figure 7.8: Isometric and Isokinetic arm curl attachment torque data for gravity correction.

7.2.2 Isometric

The validation and reliability results from the isometric positioning experiments are shown in Table 7.2, Figure 7.9 and Table 7.3 respectively. The relatively low mean error (<0.07 degrees) and standard deviation (<0.09 degrees) between the demand position, D_{pos}, and that achieved by the modular exercise system, A_{pos}, suggests that the positional mechanisms and software control programs are capable of producing accurate movements. This characteristic is reinforced by the coefficient of determination ($R^2 = 1$) which indicates that the data recorded produces an accurate relationship with the demand input.

Test number	M_{error} (degrees)	SD
1	0.037	0.062
2	0.063	0.088
3	0.058	0.078
4	0.053	0.075
5	0.053	0.075

Table 7.2: Mean error (M_{error}) and standard deviation (SD) between the demand position and the actual position achieved during isometric tests.

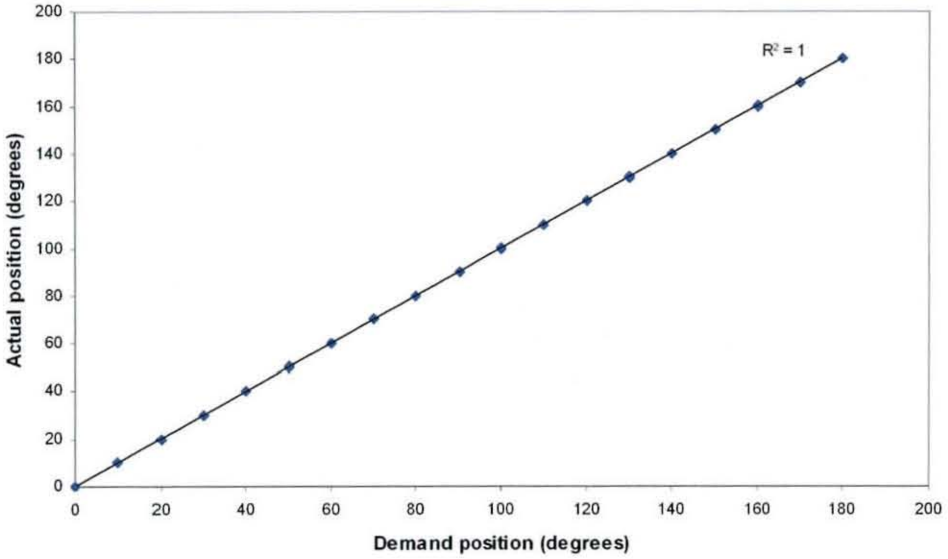


Figure 7.9: Comparative relationship between demand and actual positions.

Demand Position, D_{pos} (degrees)	Mean A_{pos} (degrees)	SD	CV (%)
0	0.000	0.000	0.000
10	10.060	0.049	0.487
20	20.080	0.040	0.199
30	30.040	0.049	0.163
40	40.060	0.049	0.122
50	50.100	0.063	0.126
60	60.060	0.049	0.082
70	70.020	0.040	0.057
80	80.060	0.049	0.061
90	90.040	0.049	0.054
100	100.060	0.049	0.049
110	110.060	0.049	0.045
120	120.040	0.049	0.041
130	130.080	0.040	0.031
140	140.040	0.049	0.035
150	150.040	0.049	0.033
160	160.020	0.040	0.025
170	170.100	0.000	0.000
180	180.040	0.049	0.027

Table 7.3: Isometric positioning reliability assessed using mean position (A_{pos}), standard deviation (SD) and coefficient of variation (CV).

Intramachine position repeatability appears to be very consistent with an average standard deviation of approximately 0.05 degrees and a negligible coefficient of variation at all positions.

The validation and reliability results from the isometric torque experiments are shown in Table 7.4, Figure 7.10 and Table 7.5 respectively. The validation results indicate that mean error is negligible (<0.4 Nm) and any deviation between the measured values, τ_{out}, and expected values, τ_{calc}, are not dependent upon the magnitude of the weight applied. The relatively high coefficient of determination (R^2 = 0.993) supports this uniform trend.

Test number	5kg Weight		10kg Weight		15kg Weight	
	M_{error} (Nm)	SD	M_{error} (Nm)	SD	M_{error} (Nm)	SD
1	0.292	0.381	0.288	0.371	0.335	0.377
2	0.346	0.486	0.341	0.406	0.335	0.423
3	0.332	0.451	0.329	0.414	0.279	0.348
4	0.312	0.406	0.290	0.375	0.298	0.389
5	0.354	0.460	0.319	0.401	0.321	0.407

Table 7.4: Mean error (M_{error}) and standard deviation (SD) between the theoretical torque and the measured torque values recorded during 5, 10 and 15kg isometric tests.

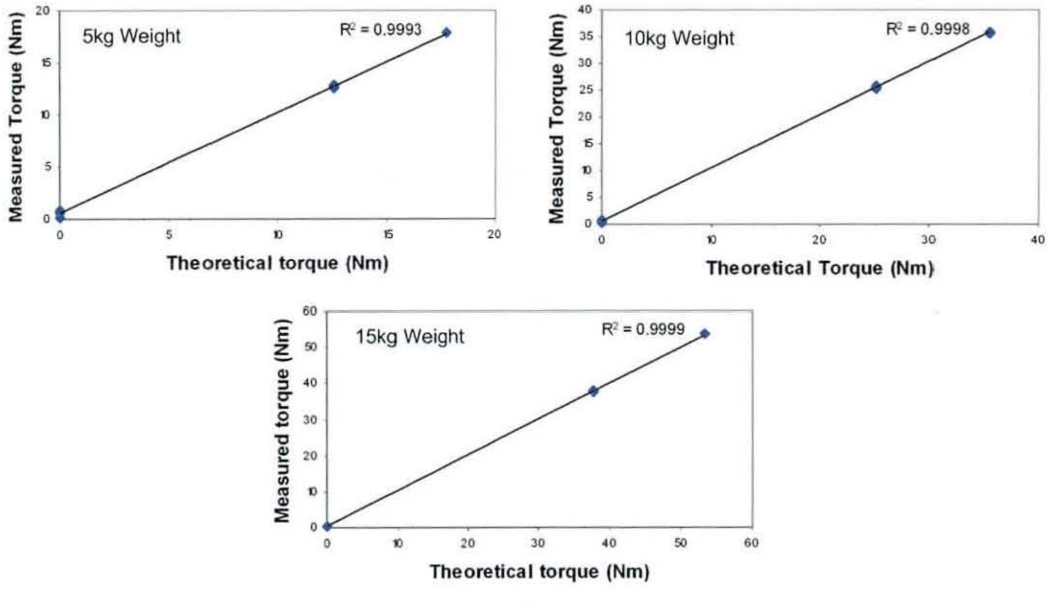


Figure 7.10: Comparative relationship between isometric theoretical and measured torque.

Position, θ_{arm} (degrees)	**5kg Weight**				**10kg Weight**				**15kg Weight**			
	τ_{calc} (Nm)	**Mean τ_{out} (Nm)**	**SD**	**CV (%)**	**τ_{calc} (Nm)**	**Mean τ_{out} (Nm)**	**SD**	**CV (%)**	**τ_{calc} (Nm)**	**Mean τ_{out} (Nm)**	**SD**	**CV (%)**
0	0.000	0.559	0.022	3.959	0.000	0.558	0.027	4.874	0.000	0.538	0.021	3.966
45	12.555	12.748	0.146	1.143	25.111	25.732	0.065	0.251	37.666	37.720	0.044	0.116
90	17.756	17.808	0.017	0.098	35.512	35.697	0.081	0.228	53.268	53.683	0.016	0.030
135	12.555	12.697	0.084	0.662	25.111	25.378	0.290	1.142	37.666	37.784	0.114	0.302
180	0.000	0.821	0.024	2.941	0.000	0.665	0.025	3.728	0.000	0.625	0.011	1.826

Table 7.5: Isometric torque measurement reliability assessed using mean torque output (τ_{out}), standard deviation (SD) and coefficient of variation (CV).

The figures in Table 7.5 indicate that the signals from the torque transducer and analogue-to-digital converter produce a reliable output. Relatively high coefficients of variation (CV >1.0%) have been found for all load conditions when the arm curl attachment was positioned in the vertically upward (0 degrees) and downward (180 degrees) orientations respectively.

7.2.3 Isokinetic

Isokinetic data for validating the modular exercise system velocity control capabilities and machine repeatability of these speeds is shown in Table 7.6, Figure 7.11 and Table 7.7 respectively. The mean velocity errors and standard deviations when the system was in the unloaded state (<0.5 degrees/s and <0.7 degrees/s) were considerably less then those recorded during the loaded experiments (<1.6 degrees/s and <1.2 degrees/s). All of the velocity values, V_{avg}, measured during the validation tests demonstrated a linear relationship with respect to the demand velocities, V_{in}. This was represented by the high coefficients of determination ($R^2 \geq 0.999$) as shown in Figure 7.11.

Test number	No Weight				20kg Weight			
	Concentric		Eccentric		Concentric		Eccentric	
	M_{error} ($^{\circ}$/s)	SD	M_{error} ($^{\circ}$/s)	SD	M_{error} ($^{\circ}$/s)	SD	M_{error} ($^{\circ}$/s)	SD
1	0.354	0.501	0.089	0.591	1.533	0.898	1.022	0.812
2	0.132	0.156	0.463	0.390	1.386	0.872	0.852	0.836
3	0.140	0.556	0.043	0.630	1.581	0.974	0.887	0.842
4	0.215	0.184	0.463	0.390	1.256	0.722	1.344	1.168
5	0.205	0.528	0.480	0.362	1.402	0.819	1.237	0.863

Table 7.6: Mean error (M_{error}) and standard deviation (SD) between the demand velocity and the measured velocity values recorded during un-weighted and weighted isokinetic tests.

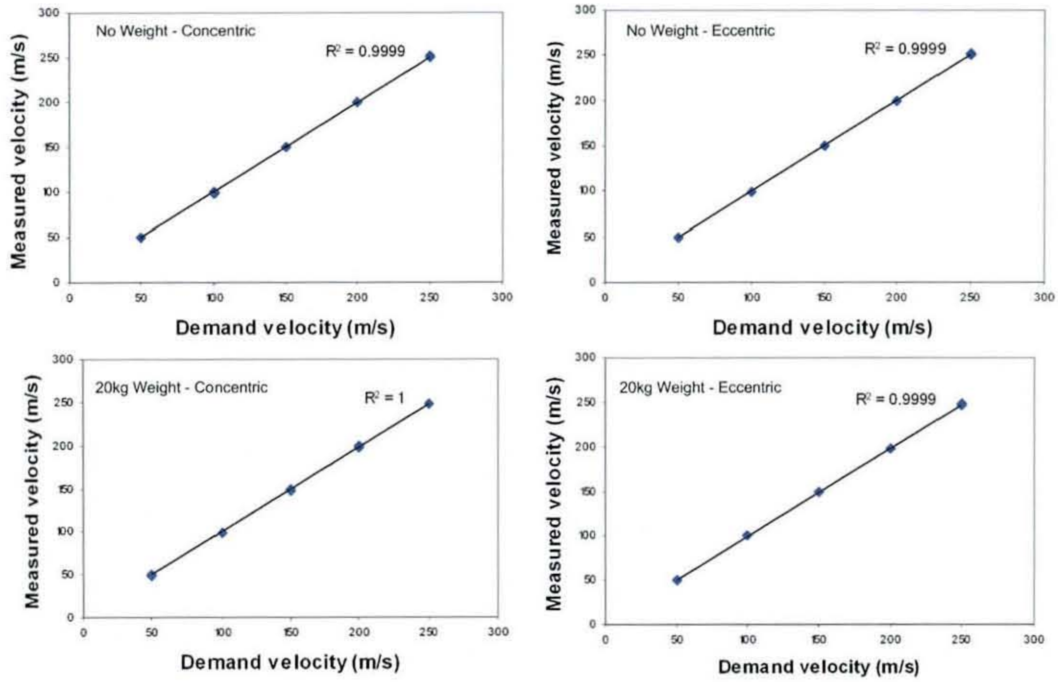


Figure 7.11: Comparative relationship between demand and measured velocity in concentric and eccentric movement directions.

Demand velocity, V_{in} (m/s)	No Weight						20kg Weight					
	Concentric			Eccentric			Concentric			Eccentric		
	Mean V_{avg} (m/s)	SD	CV (%)	Mean V_{avg} (m/s)	SD	CV (%)	Mean V_{avg} (m/s)	SD	CV (%)	Mean V_{avg} (m/s)	SD	CV (%)
50	49.752	0.202	0.407	49.917	0.165	0.331	49.588	0.259	0.523	50.179	0.220	0.438
100	99.338	0.208	0.209	99.147	0.168	0.170	99.207	0.263	0.265	100.403	0.330	0.329
150	150.160	0.320	0.213	150.164	0.193	0.128	148.222	0.358	0.242	149.106	0.296	0.198
200	200.260	0.520	0.260	199.135	0.454	0.228	197.891	0.640	0.324	197.568	0.400	0.202
250	251.261	1.029	0.410	250.840	1.029	0.410	248.134	0.748	0.302	247.527	0.813	0.328

Table 7.7: Isokinetic velocity reliability assessed using mean velocity (V_{avg}), standard deviation (SD) and coefficient of variation (CV).

The standard deviation (> 1.1 degrees/s) and coefficient of variation (> 0.53%) figures calculated from the reliability tests indicate that the machine repeatability is very good. However, the magnitude of variation between the tests increases with the demand velocity in both loaded and unloaded conditions (see Table 7.7).

Isokinetic torque validation and reliability data is shown in Table 7.8, Figure 7.12 and Table 7.9. The mean error and standard deviation values between the theoretical torque, τ_{calc}, and the output torque, τ_{out}, are of a similar magnitude to those determined during the isometric tests (see Table 7.4). The increased distribution of values can be seen in Figure 7.12 although the linear correlation trend between the recorded and calculated torque data is clear with a high coefficient of determination ($R^2 > 0.97$).

Test number	5kg Weight		10kg Weight		15kg Weight	
	M_{error} (Nm)	SD	M_{error} (Nm)	SD	M_{error} (Nm)	SD
1	0.548	0.658	0.632	0.823	0.359	0.786
2	0.518	0.578	0.482	0.777	0.352	0.784
3	0.500	0.570	0.524	0.715	0.551	0.793
4	0.642	0.679	0.684	0.761	0.533	0.783
5	0.672	0.712	0.639	0.726	0.397	0.750

Table 7.8: Mean error (M_{error}) and standard deviation (SD) between the theoretical torque and the output torque values recorded during weighted isokinetic tests.

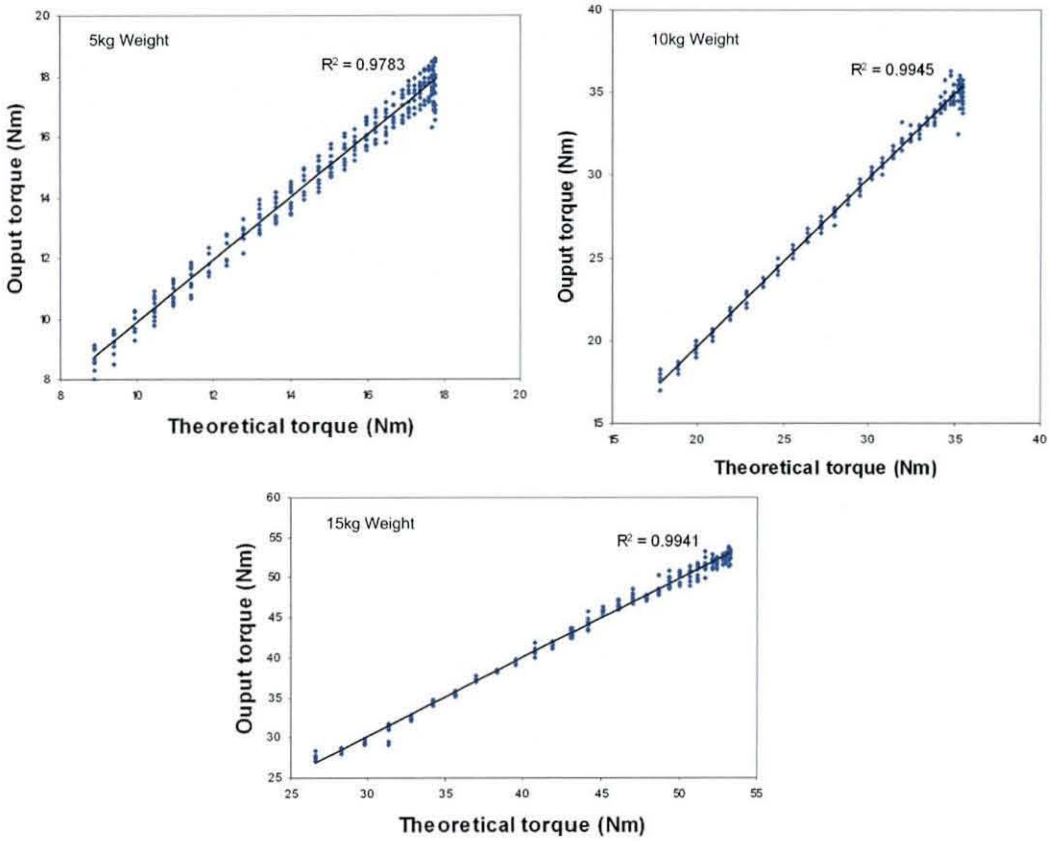


Figure 7.12: Comparative relationship between theoretical torque and output torque during a complete isokinetic repetition.

Position, θ_{arm} (degrees)	5kg Weight				10kg Weight				15kg Weight			
	τ_{calc} (Nm)	Mean τ_{out} (Nm)	SD	CV (%)	τ_{calc} (Nm)	Mean τ_{out} (Nm)	SD	CV (%)	τ_{calc} (Nm)	Mean τ_{out} (Nm)	SD	CV (%)
30	8.878	9.079	0.264	2.911	17.756	17.873	0.371	2.075	26.634	27.897	0.247	0.884
40	11.413	11.781	0.268	2.279	22.827	23.290	0.243	1.042	34.240	34.847	0.340	0.975
50	13.602	14.047	0.257	1.833	27.204	27.702	0.281	1.014	40.806	40.868	0.297	0.727
60	15.377	16.006	0.377	2.359	30.754	31.447	0.348	1.106	46.132	47.260	0.469	0.993
70	16.685	17.345	0.343	1.976	33.371	34.063	0.192	0.564	50.056	50.937	0.663	1.302
80	17.486	18.399	0.560	3.045	34.973	35.756	0.417	1.166	52.459	52.590	0.525	0.999
90	17.756	18.145	0.332	1.832	35.512	35.807	0.417	1.164	53.268	53.602	0.350	0.652
100	17.486	18.264	0.506	2.768	34.973	35.689	0.183	0.513	52.459	52.582	0.348	0.662
110	16.685	17.356	0.342	1.968	33.371	34.166	0.103	0.300	50.056	50.423	0.578	1.146
120	15.377	16.041	0.300	1.873	30.754	31.293	0.281	0.898	46.132	46.991	0.197	0.419
130	13.602	14.188	0.274	1.928	27.204	27.784	0.278	1.002	40.806	41.441	0.568	1.371
140	11.413	11.767	0.235	1.993	22.827	22.777	0.299	1.313	34.240	34.661	0.295	0.851
150	8.878	9.365	0.252	2.688	17.756	18.630	0.164	0.878	26.634	28.328	0.382	1.348

Table 7.9: Isokinetic torque measurement reliability assessed using mean torque (τ_{out}), standard deviation (SD) and coefficient of variation (CV).

The isokinetic torque measurement reliability (i.e. variation in measurements) characteristics also appear to correlate closely with the data collected during the isometric experiments. Comparatively low standard deviations (< 0.7 Nm) and coefficients of variation (< 3.1%) suggest that the torque transducer and analogue-to-digital converter are not adversely affected by the drive movement during an isokinetic exercise.

7.2.4 Isotonic

The validity and reliability data from the isotonic torque production experiments is shown in Table 7.10, Figure 7.13 and Table 7.11 respectively.

Test number	M_{error} (Nm)	SD
1	1.554	1.879
2	1.493	1.787
3	1.493	1.820
4	1.554	1.854
5	1.433	1.698

Table 7.10: Mean error (M_{error}) and standard deviation (SD) between the demand torque and the output torque values recorded during isotonic tests.

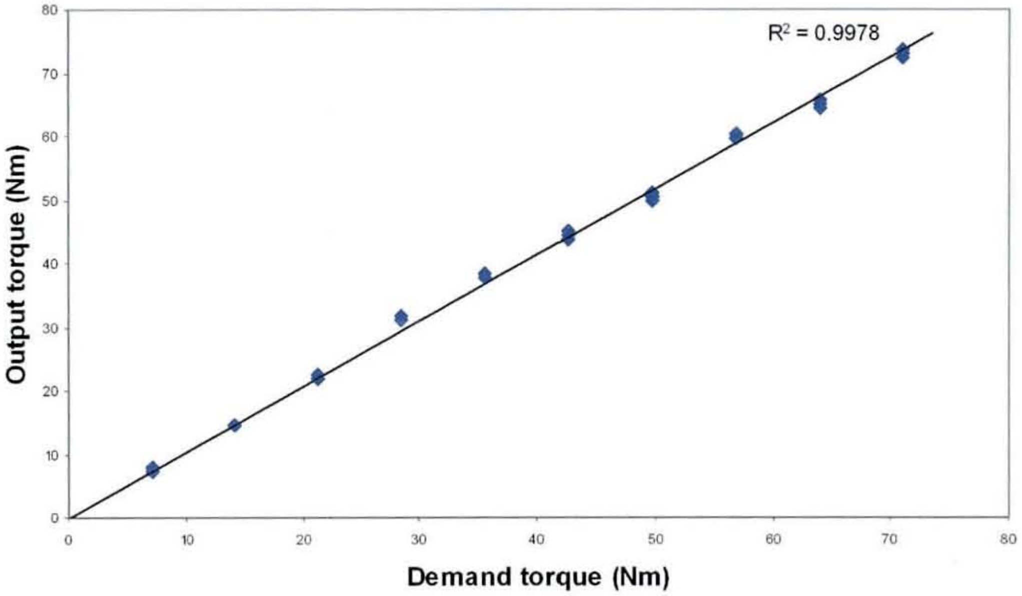


Figure 7.13: Comparative relationship between demand and output torque during isotonic exercise.

Weight, W_{in} (kg)	**τ_{in} (Nm)**	**Mean τ_{out} (Nm)**	**SD**	**CV (%)**
2	7.102	7.531	0.001	0.013
4	14.205	14.641	0.110	0.754
6	21.307	22.006	0.157	0.719
8	28.410	31.251	0.298	0.953
10	35.512	37.941	0.298	0.785
12	42.615	44.145	0.237	0.539
14	49.717	50.349	0.455	0.904
16	56.820	59.716	0.243	0.407
18	63.922	65.068	0.385	0.591
20	71.024	73.097	0.455	0.623

Table 7.11: Isotonic torque production reliability assessed using mean torque (τ_{out}), standard deviation (SD) and coefficient of variation (CV).

Mean error and standard deviation between the demand torque, τ_{in}, and output torque, τ_{out}, was consistent between trials as demonstrated by the high coefficient of determination ($R^2 = 0.9978$). Machine reliability results suggest that repeated force production during different tests produces a uniform output with low standard deviation (<0.5 Nm) and coefficient of variation (<1.0 %). Also it appears that the reliability of the output torque production is not influenced by the magnitude of the demand torque.

7.2.5 User performance data

The data presented in this section represents actual performance results recorded by the modular exercise system during the pre-determined exercise sessions (see section 7.1.5). The mean torque versus time relationships at five different joint positions during three isometric repetitions are shown in Figure 7.14. A rapid increase in torque can be seen at all positions during the initial phase of the exercise (time < 1sec) which subsequently taper into an approximately level output.

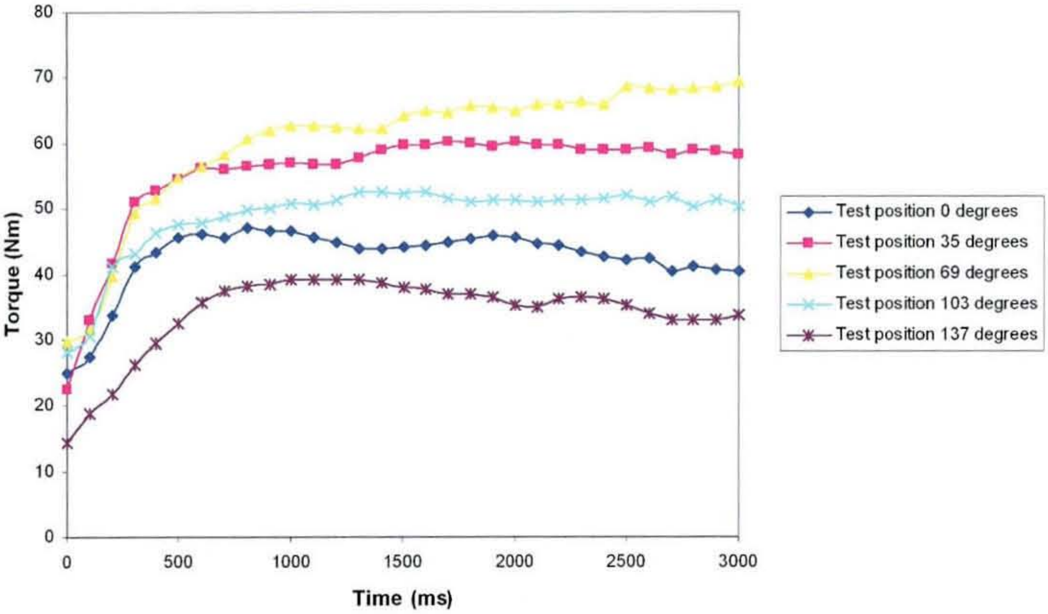


Figure 7.14: Mean torque vs. time results recorded during repeat isometric exercises.

The torque versus position relationship has been determined by calculating the average torque over the complete contraction period. The mean torque value for each repetition has been plotted against the test location as shown is Figure 7.15. The results show that maximum torque is experienced at the 69 degree test position.

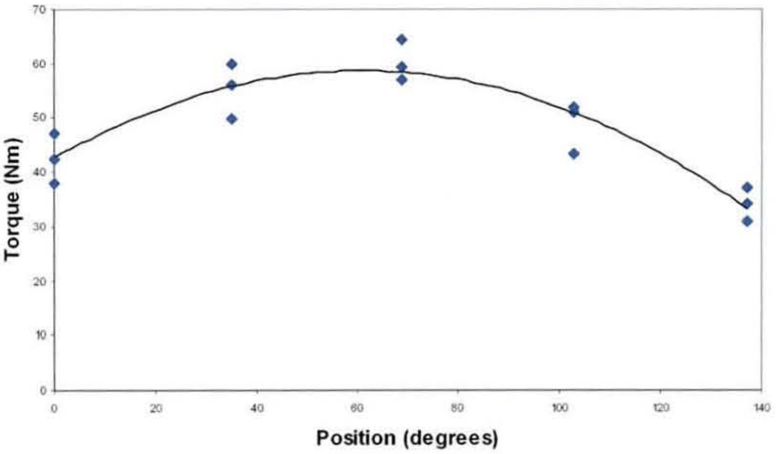


Figure 7.15: Mean torque vs. position results recorded during repeat isometric exercises.

The variation of torque with regard to position for the chosen subject during concentric and eccentric isokinetic exercises is shown in Figure 7.16 and Figure 7.17

respectively. Both concentric and eccentric results exhibit a parabola style relationship with maximum torque values corresponding to test positions around 65 to 75 degrees. This trend supports the results collected during the isometric tests. Maximum eccentric torque data (approximately 72 Nm) exceeds that which was collected during the concentric tests (approximately 52 Nm) at all positions.

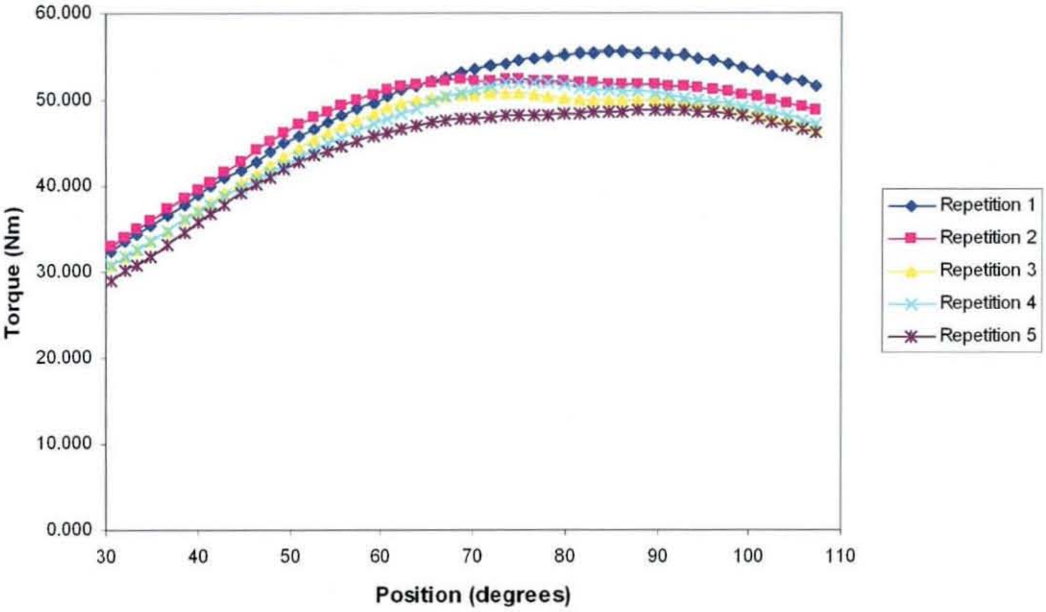


Figure 7.16: Torque vs. position results recorded during five concentric isokinetic exercises.

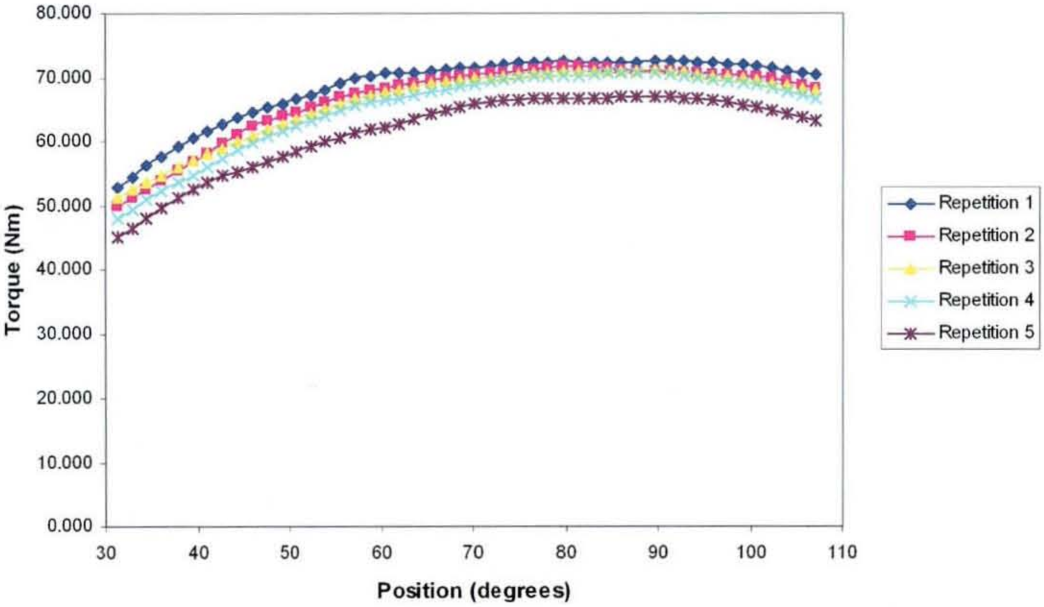


Figure 7.17: Torque vs. position results recorded during five eccentric isokinetic exercises.

The results shown in Figure 7.18 represent the torque versus position relationship for five isotonic repetitions, where a single repetition consists of a raising and lowering action. The trend illustrated in these results does not follow the linear input profile that was applied to the subject during the exercise. Clear deviations between input torque and recorded torque (max deviation < ± 12 Nm) can be seen at the beginning of both the raising and lowering phases.

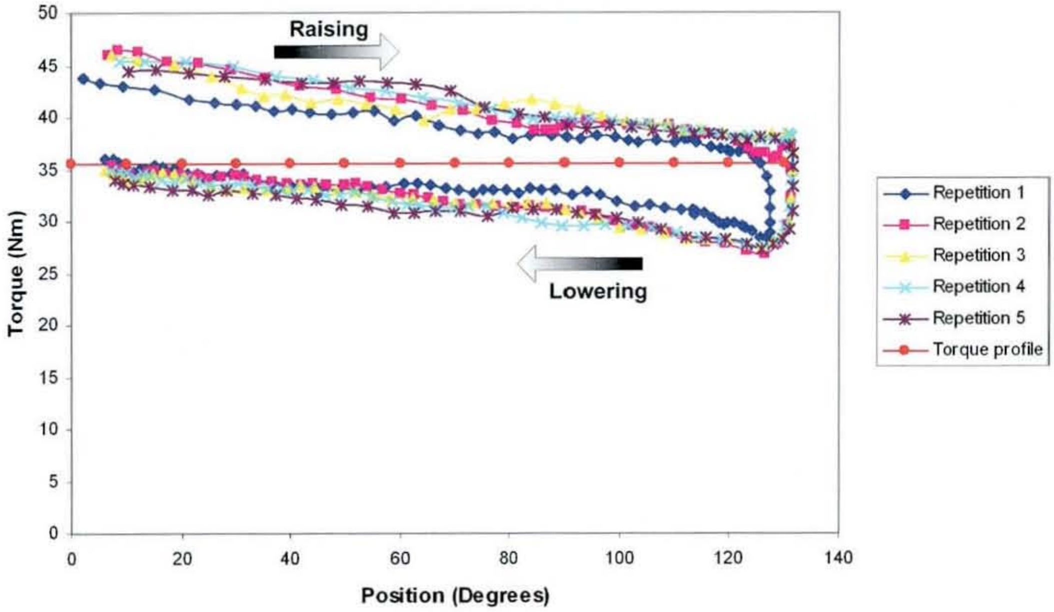


Figure 7.18: Torque vs. position results recorded during five isotonic exercises.

An arbitrary profile was implemented during the isotonic tests shown in Figure 7.19. The output torque is plotted against position and is shown with the input profile for comparison purposes. A definite correlation can be identified between the input signal and the resultant output torque values during both the raising and lowering phases. However, a torque offset difference (max deviation < ± 10 Nm) has been shown to exist which was also identified during the standard isotonic exercise.

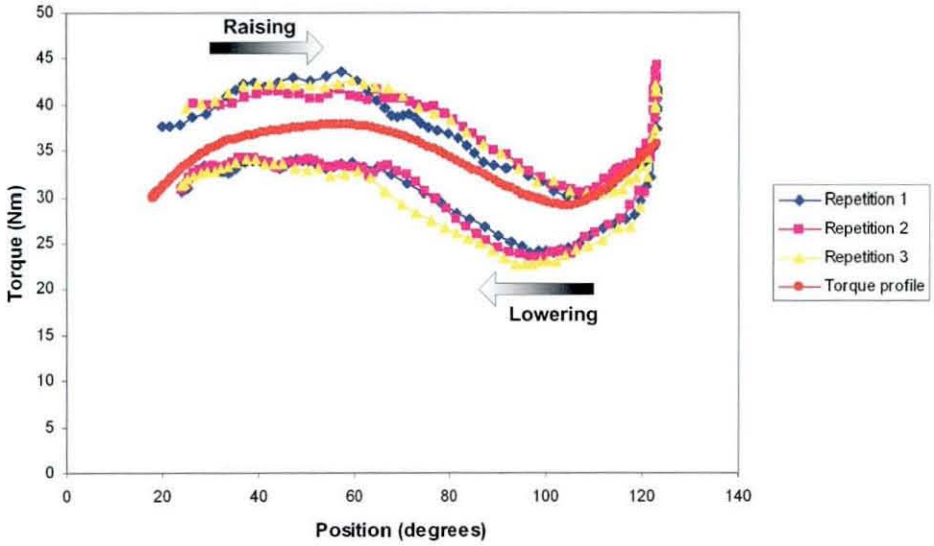


Figure 7.19: Torque vs. position results recorded during three profiled isotonic exercises.

The effect of adding "virtual inertia" to the 10 kg weight specified during the basic isotonic exercise (see Figure 7.18) using the modular exercise program software is shown in Figure 7.20. The basic profile has been shown together with the resultant torque recorded during three complete repetitions. The inertial influence has caused an increase in torque at the beginning of the lifting phase and end of the lowering phase when compared to the standard isotonic torque versus position relationship. This program has also produced a reduction in torque at the end of the raising phase and beginning of the lowering phase.

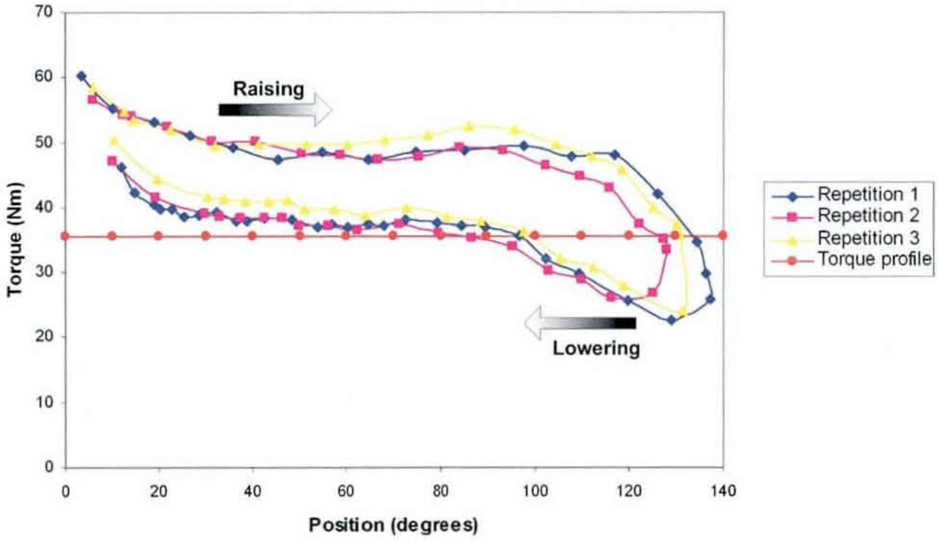


Figure 7.20: Torque vs. position results recorded during three "virtual inertia" isotonic exercises.

The velocity and torque data recorded during the variokinetic tests are shown in Figure 7.21 and Figure 7.22 respectively. These results represent the information collected during single concentric variokinetic exercises. The demand velocity and torque profiles have been included in each of the graphs for comparison.

The inability of the user to match the required velocity (see Figure 7.21) throughout the whole movement has resulted in an automatic adjustment in the applied torque as implemented in the variokinetic software program (see Chapter 6). This variation in velocity has produced the irregular torque versus position relationship as shown in Figure 7.22.

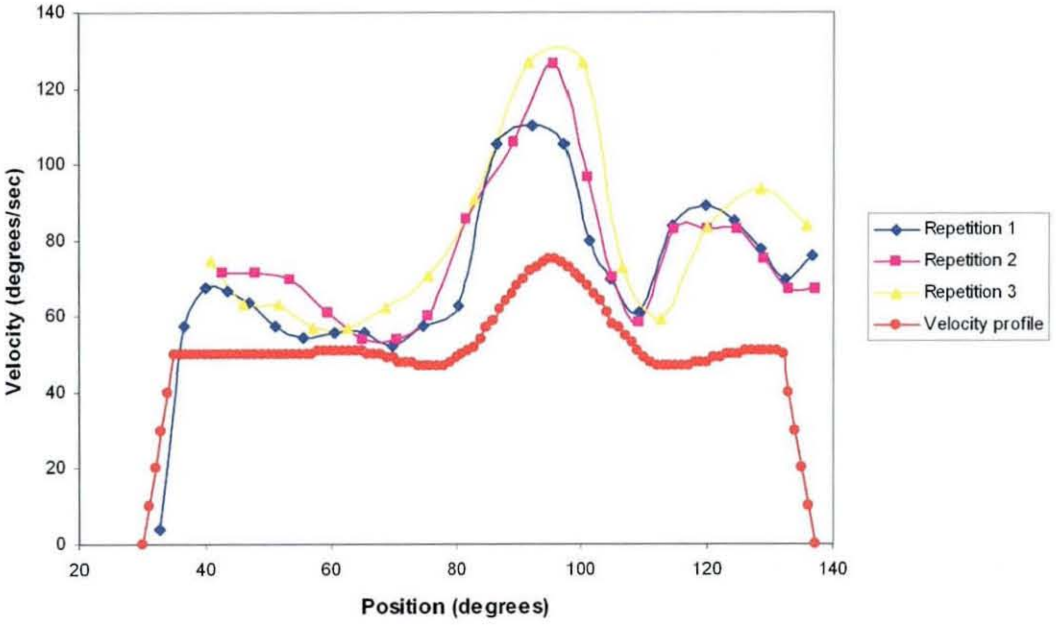


Figure 7.21: Velocity vs. position results recorded during three variokinetic concentric exercises.

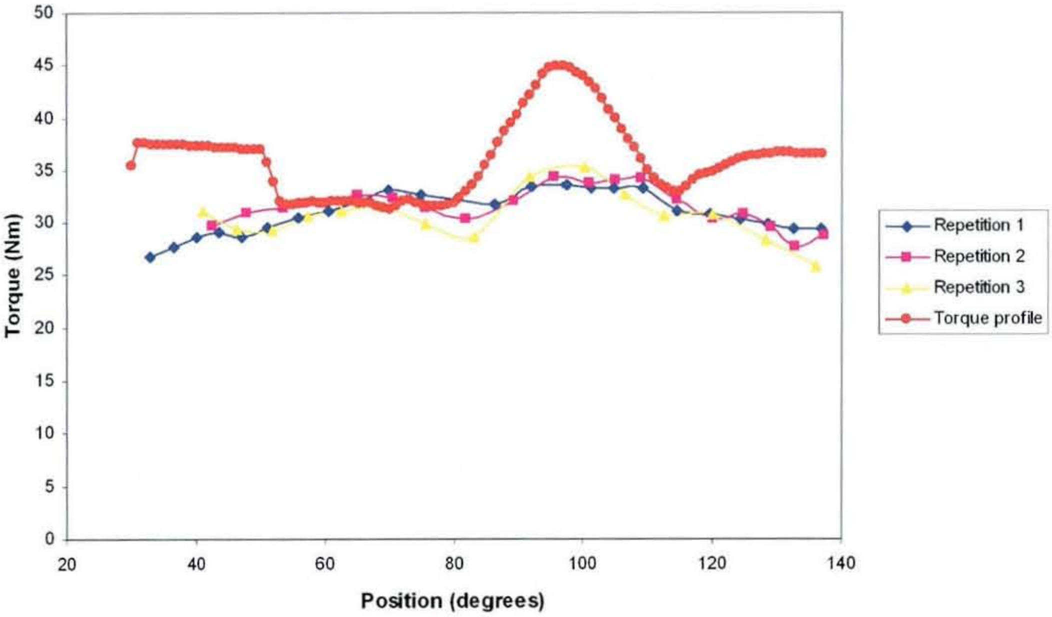


Figure 7.22: Torque vs. position results recorded during three variokinetic concentric exercises.

7.3 Discussions

The validation and reliability data collected during this research demonstrates that the hardware and software elements of the modular exercise system can produce accurate and repeatable exercise stimulus and performance feedback. The results recorded during subject testing produced standard output trends and normative peak values which suggest that the modular exercise system is a viable training tool. The information determined from these tests is discussed in detail in the following sections.

7.3.1 Validation and reliability data

The isometric position data shown in Table 7.2 and Figure 7.9 indicated an excellent coherence between the demand position, D_{pos}, and the actual position, A_{pos}, acquired as measured using the hand held inclinometer. The mean error between the five trails never exceeded 0.1 degrees which compares very favourably with isokinetic dynamometer positioning data (Drouin *et al.*, 2004). Machine reliability between repeat positions was also found to be markedly consistent with a maximum standard deviation of 0.063 degrees at a position of 50 degrees. This level of positional precision can be attributed to the accuracy of the integrated resolver unit which provides measurements within a 0.008 degree tolerance band and the zero backlash couplings used throughout the transmission system which eliminate undesirable torsional movement.

The torque data recorded during the pre-loaded isometric experiments suggest that the modular exercise system is capable of producing accurate results as shown in Table 7.4 and Figure 7.10. The mean error between the theoretical torque, τ_{calc}, and the values measured using the torque transducer and analogue-to-digital conversion systems, τ_{out}, was less then 0.4 Nm. This level of precision is similar to that determined for existing isokinetic dynamometers which was deemed acceptable for credible measurement of human performance (Durin *et al.*, 2004; Farrel & Richards, 1986).

The machine reliability data as shown in Table 7.5 produced slightly higher levels of variance than the validation data but these values were small (SD < 0.29 Nm and CV < 4%) and thus would not result in significant errors. Relatively high coefficient of variation values were identified at actuator positions of 0 and 180 degrees. The theoretical calculations suggested that torque output should be zero at these locations. However, during the test procedures torque offset signals were recorded above this datum level. This could be attributed to imbalance in the cast iron weights which were applied to the arm curl attachment. Any variation in the centre of mass of these weights could result in the creation of a small bending moment about the centre of rotation. This moment will impart a torsional load onto the torque transducer and thus produce a small output reading.

The statistical measures of validity of the isokinetic velocity measurements, over the range of velocities tested, are of a similar magnitude (mean error < 1.6 degree/s) to those determine for commercial isokinetic dynamometers (mean error > 2.94 degree/s)(Bemben *et al.*, 1988; Dillon *et al.*, 1998; Drouin *et al.*, 2004). This level of accuracy, as shown in Table 7.6 and Figure 7.11, is considered as acceptable for clinical and research testing and appeared to be independent of movement direction or applied load. Reliability data was found to produce high levels of uniformity between the measured velocities, V_{avg}, and demand velocity, V_{in}, entered into the exercise system software as shown in Table 7.7. Standard deviation and coefficient of variation measures were not influenced by movement direction or applied load but an increasing trend was identified in relation to the magnitude of the velocity. This trend has also been identified in previous velocity studies (Drouin *et al.*, 2004) although the error level was deemed as acceptable. It has been proposed that this effect could be due to the increased torque requirements to accelerate the arm attachment to the desired velocity and the time taken for the control loop to attenuate the resultant velocity to a constant level.

Isokinetic torque validation data suggests that the modular exercise system is capable of producing performance assessment results (mean error < 0.7 Nm) which are more accurate then those recorded using commercially available isokinetic dynamometers (average mean error 8 Nm)(Farrel & Richards, 1986). Both validation and reliability statistics, shown in Table 7.8, Figure 7.12 and Table 7.9 respectively, do not appear to be dependent upon the magnitude of the load applied or the direction of the movement. The coefficients of variation are notably higher when testing with the lower weight as the relative difference in measurements is considerably higher. At these lower torque levels, the resolution of the torque transducer and the analogue-to-digital conversion could influence the magnitude of the error since the measured values are within the accuracy range of the respective systems. Therefore, the measurement and cross-correlation of performance records at these lower force levels should take this limiting factor into consideration.

The isotonic torque validation statistics indicate that the modular exercise system is capable of producing a representative load to replicate a standard free weight or selectorised weights machine as shown in Table 7.10 and Figure 7.13. The mean error between the theoretical torque, τ_{in}, and the applied torque, τ_{out}, was found to be slightly higher (<1.6 Nm) than that determined during the isometric (<0.4 Nm) and isokinetic (<0.7 Nm) torque measurement experiments. This additional level of torque could be a result of under correction of the gravitation effect of the out of balance mass of the arm curl attachment. The internal torque control loop of the motor controller will compensate for this deficit by applying an offset to the output signal. However, the magnitude of variation appears to be within the mass variation found with typical free weight plates. The intramachine reliability of the torque generation facility was found to be relatively consistent regardless of the applied load with a maximum standard deviation of 0.5 Nm as shown in Table 7.11.

7.3.2 User performance data

Regardless of the isometric test position, the torque applied by the user exhibits a rapid increase at the onset of the exercise and appears to reach a peak value within a similar time period (1 sec) as shown in Figure 7.14. These torque versus time relationships demonstrate similar characteristics to those established in existing isometric force production experiments (Holterman *et al.*, 2007). The average of these torque values over the contraction period were plotted in relation to the test position as shown in Figure 7.15. These values have been corrected for the gravitation effect of the actuator and therefore represent the actual performance capabilities of the muscle group under investigation. The relationship demonstrated in this graph shows good correlation to that which would be expected from previous research (Knapik *et al.*, 1983). A curved response which peaks at approximately 90 degrees is a common characteristic found in arm flexion with a maximal value around 75 Nm (Knapik *et al.*, 1983). The similarities between the measured values and those found in research literature suggest that the tests are producing reliable information.

The variation of torque with position for the chosen subject during concentric and eccentric isokinetic exercises is shown in Figures 7.16 and 7.17 respectively. These data exhibit the key performance features that are expected from such an experiment (Knapik *et al.*, 1983). A parabola style curve with a peak torque value which corresponds to a position of 60 to 70 degrees supports the results found during the isometric tests and matches the trends found in previous research (Knapik *et al.*, 1983). Maximum eccentric torque exceeds the relative concentric value (approximately + 35%) as would be expected (Hortobagyi & Katch, 1990) and the concentric torque magnitude is less than that recorded during the isometric tests (approximately -40%)(Knapik *et al.*, 1983). These cross-correlation relationships suggest that the isokinetic performance monitoring capabilities of the modular exercise system are comparable to those exhibited by existing dynamometers.

The torque recorded during five isotonic repetitions at a load of 10 kg are shown in Figure 7.18, where a single repetition consists of a raising and lowering action between the upper and lower limits of motion. During the raising phase of the exercise the recorded torque decreases from a maximum offset of approximately 10Nm to the demand value at the end of the movement. This is a result of the inertial effect of the arm curl attachment and the additional force that is required to overcome the applied resistance in order to lift the "weight". As the user begins to lower the actuator a substantial decrease in torque is experienced as the system is allowed to accelerate without resistance. As the user applies a force to control the velocity of the lowering motion, the recorded torque increases. Maximum torque recorded during the lowering phase occurs as the user decelerates the actuator as they approach the limit of motion.

Assuming that the out of balance mass of the actuator (4.5 kg) determined during the gravity correction experiments (see section 7.2.1) acts as a point load at a position approximately half way along its length (i.e. 0.16 m), the result torque, $\tau_{inertia}$, due to inertial effects of acceleration, α ,during the exercise can be estimated:

$$\tau_{inertia} = (m \times l^2) \times \alpha \tag{7.2}$$

There is a lack of data regarding the angular accelerations that occur during a bicep curl exercise. Therefore, a maximum angular velocity of 300 degrees per second (Perrin, 1993) is assumed, over a 150 degree range of motion, and with constant acceleration and deceleration from and to zero angular velocity. The angular acceleration is calculated using the equation below:

$$\omega^2 = \omega_0^2 + 2 * \alpha * (\theta - \theta_0) \tag{7.3}$$

where: ω = angular velocity (radians/s)

ω_0 = initial angular velocity (radians/s)

α = angular acceleration (radians/s^2)

θ = angular position (radians)

θ_0 = initial angular position (radians)

$$\therefore 5.236^2 = 0^2 + 2 * \alpha * (1.309 - 0)$$

$$\alpha = 10.47 \text{ radians/s}^2$$

The resultant torque due to linear acceleration of the arm curl attachment is shown in Figure 7.23. This estimation illustrates a good correlation with the data collected during the isotonic tests. This inertial effect can also be identified when the subject was instructed to exercise against the profiled load as shown in Figure 7.19. Clear deviations can be seen between the input load and measured torque at the beginning of the both the raising and lowering phases. This difference is significantly reduced at the end of these movements. The rapid increase in measured torque at the upper limit of motion is a result of the isotonic software "virtual limit stop" (see Chapter 5, section 5.3.8). This function applies an exponential factoring algorithm to the applied load which is designed to prevent the user from activating the electromechanical stops which would otherwise cause a system emergency stop. Due to the nature of the profile the subject found it difficult to control the motion at the upper limit and therefore was unable to prevent the actuator from entering this threshold area.

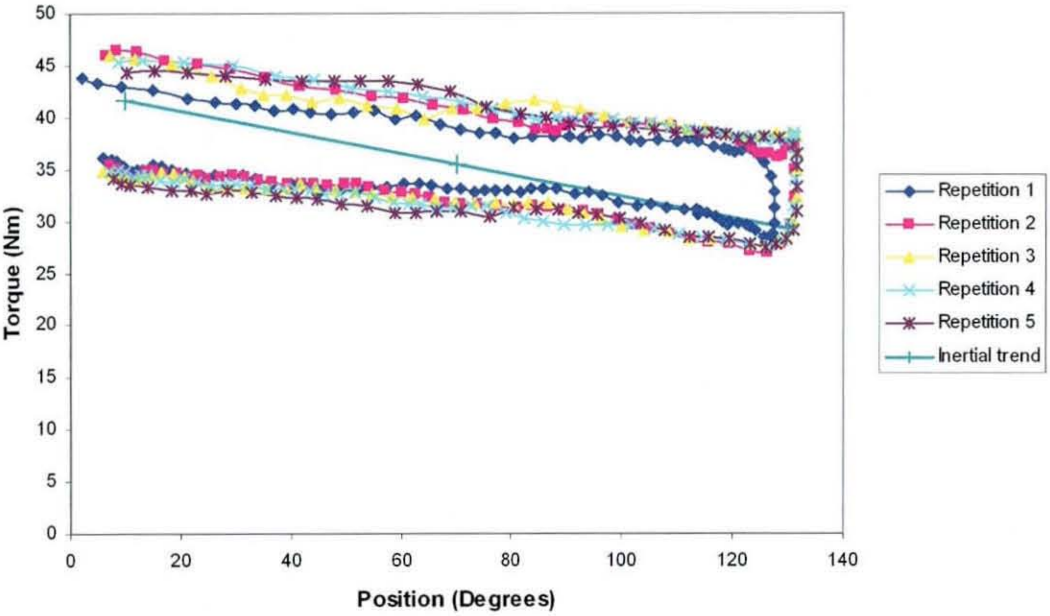


Figure 7.23: Torque vs. position results recorded during the isotonic exercises including the approximated inertial profile for the actuator.

The effect of adding "virtual inertia" to the 10 kg load specified during the basic isotonic exercise is shown in Figure 7.20. When the torque versus position relationship recorded during this setup is compared to the first set of experiments it is clear that the acceleration and deceleration during the move is having an effect upon the load experienced (compare figures 7.20 and 7.18). The variation in resistance follows a similar trend to that which was proposed during the literature review (see Chapter 2, section 2.2.2). Using the angular accelerations and assumptions for the standard isotonic test, the inertial effect of this virtual load have been estimated as shown in Figure 7.24.

The relationship demonstrated in Figure 7.24 suggests that the modular exercise system isotonic software program is capable of producing resistance profiles that can be altered in real time which represent the inertial effects experienced with standard weight training equipment. However, additional development is required to accurately quantify the acceleration during these movements to ensure the system is applying the correct inertial load.

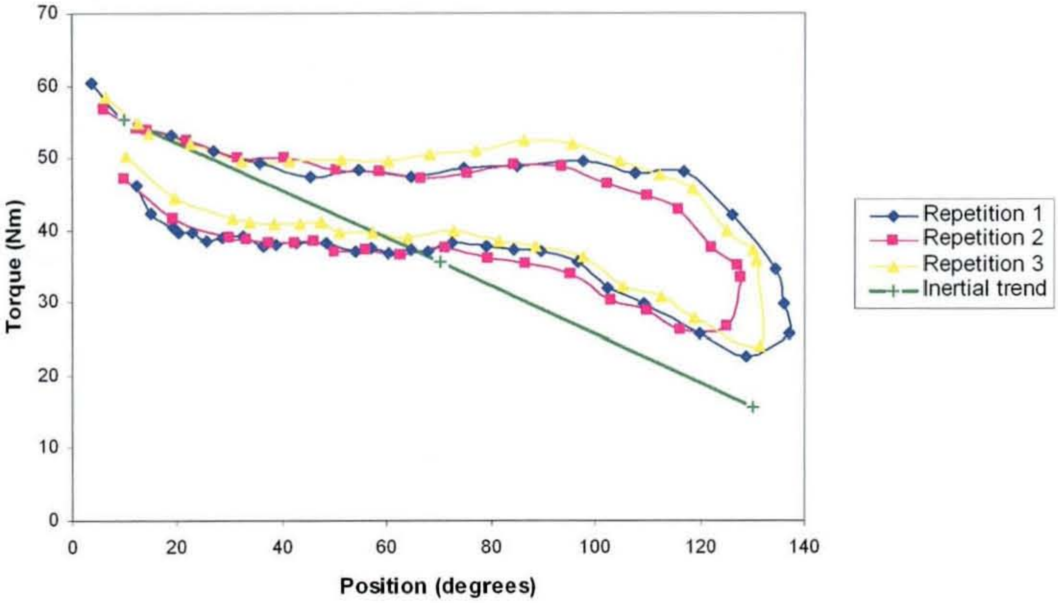


Figure 7.24: Torque vs. position results recorded during three "virtual inertia" including an approximate inertial profile for the specified weight.

Given that variokinetic exercise is a completely original training mode, the data collected during the subject tests can not be cross referenced against existing research studies. However, the basic of operation of the system can be assessed by comparing the measured velocity and torque data to the input profiles as shown in Figure 7.25. At points V_A, V_C and V_E, the actual velocity of the actuator during the repetitions was above the demand value. As discussed in Chapter 5, a positive difference in velocity will cause a reduction in the applied force which can be seen at points τ_A, τ_C and τ_E. During the periods when the actual velocity matches the demand velocity, points V_B and V_D, the applied torque follows the demand profile, τ_B and τ_D. Therefore, in principle it appears that the variokinetic software program is producing the desired functionality. However, additional testing is required to accurately evaluate the effects of velocity upon the applied torque using different variokinetic variable values in a systematic and controlled manner. During testing, the subject reported that the movement experienced during the experimental repetitions was unexpected and therefore they found it difficult to acquire the desired velocities. If additional subject testing is to be conducted it is recommended that comprehensive familiarisation trails are conducted to avoid erroneous data collection.

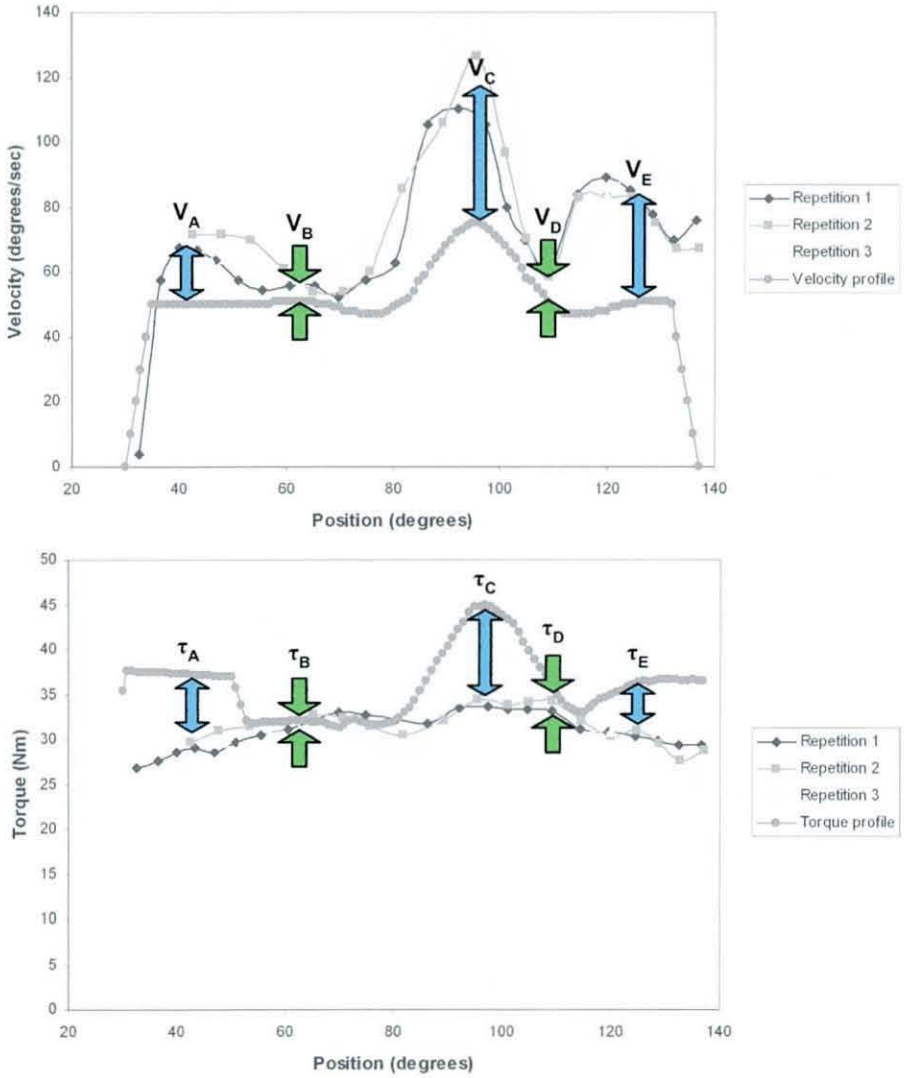


Figure 7.25: Automatic torque adjustments made with respect to input velocity during the variokinetic concentric exercises.

7.4 Summary

If the modular exercise system platform developed during this research is to be considered as a viable alternative to existing training devices it is important that the measurement capabilities and exercise functionality of the software and hardware components are defined. A series of controlled tests were developed to investigate the validity and repeatability of the fundamental input and output variables using independent instrumentation and analytical models. Positional accuracy, dynamic and static torque measurement, velocity control and torque control were assessed during these experiments. Small deviation between results is unavoidable due to internal friction and torsional twist in the drive transmission elements and the inherent accuracy of the integrated measurement devices. However, statistical analysis of the results suggests that the data recording facilities of the modular exercise system are as accurate or provide additional levels of precision when compared to equivalent indices determined for existing commercial isokinetic dynamometers. The motion generation parameter measurements of velocity and torque demonstrated excellent correlation with the demand values. Machine reliability during all of the test procedures indicated a high level of repeatability between multiple trials. Further validation and reliability tests could be conducted using different anaerobic or aerobic attachments although the fundamental motion variables and measurement parameters will be identical to those investigated during these experiments.

A series of user performance tests were also conducted to compare the output of the modular exercise system with data collected during existing research studies and clinical assessments. Isometric torque versus time, isometric torque versus position and isokinetic torque versus position relationships determined for the test subject demonstrated the key trends and peak parameter magnitudes that were as predicted from the literature. Isotonic weight simulation was shown to produce a realistic level of resistance and the ability to implement a varied load profile was demonstrated successfully. The gross effect of the "virtual inertia" option was shown to produce the expected alterations in the basic isotonic torque output although additional testing is required to quantify the acceleration that is experienced during each test and thus enable the inertia of the actuator to be removed from the resultant measurements. The example variokinetic exercise demonstrated the real time, velocity related, torque adjustment characteristics of this novel training mode. However, further comprehensive tests are required to fully investigate the effect of the individual elements of the torque correction algorithms and reference data upon the applied torque in relation to the measured velocity discrepancy.

Chapter 8

Conclusions and recommendations for further research

8.0 Research review

The aim of this Ph. D. research was to develop a novel training system which would provide a step change in functionality, safety and ease of use. A series of research questions were proposed at the initiation of this study and the results of the work completed are discussed below in relation to these primary objectives:

> **Research question 1 -** *What training methods and exercise approaches exist for improving general health and sporting performance?*

A thorough investigation of exercise science fundamentals was undertaken to identify the primary components of human motion. Anatomical, physiological and biomechanical characteristics which influence performance and are modified by exercise stimulus were established. Muscular actions during exercise were categorised according to existing literature definitions as isometric, isokinetic and isotonic. A novel exercise mode has been proposed, termed variokinetic, which introduces the concept of variable motion velocity and applied torque. This mode should increase the realism of sport specific movement simulations and also provide the capabilities to reproduce movement patterns in everyday activities. The acute training variables and organisation structures associated with each of these exercises were examined to determine the key input parameters of the modular exercise system.

Research question 2 - *What are the influential factors of exercise equipment design in determining user participation and motivation?*

A critical evaluation of historical and state of the art anaerobic and aerobic exercise equipment was conducted to highlight positive features and inherent problems in the design and operation of these systems. Current state of the art isokinetic dynamometer devices were found to be complex to operate and configure, with specialist user interfaces. A detailed quantitative analysis was conducted to determine the maximum resistance parameters of each device in order to identify the optimal performance requirements for the modular exercise system. This information was collated together with general user requirements and industry standards and legislation to produce a detailed design specification document. This document outlined the overall operational aspects of the multi function exercise system which would provide existing resistance training outputs but would also produce isotonic profiled loads, inertial loading, variokinetic and aerobic exercises from a single resistance unit.

Research question 3 - *How can the operation of exercise equipment be improved by utilising formalised systems modelling concepts?*

Systems modelling techniques have been used previously to illustrate the operational aspects of research and commercial exercise devices but these examples were found to be complex, unstructured and semantically imprecise. In order to aid the development of the modular exercise system a systematic review of systems modelling techniques was conducted to identify a method that could be used to capture and present information relating to a multi faceted machine such as that proposed. The computer integrated manufacturing open systems architecture (CIMOSA) enterprise modelling approach was eventually selected from the candidate approaches. This method was selected as the underlying process orientated concepts were found to be analogous to the operational requirements of the exercise system. A complete systems model was created during the initial stages of the research and the individual diagrams were subsequently used in the implementation of both software and hardware systems. The information stored in these formalised and structured models was found to be an invaluable resource during the development process and therefore this implementation must be considered as evidence of the success of cross-discipline applications of this methodology.

> **Research question 4** - *How can existing technologies be utilised in the creation of an advanced training system which demonstrates the appropriate exercise modes established in research question 1 and operational requirements from research question 3?*

Development of the modular exercise system was divided into two main elements: software and hardware. The hardware design and production process was decomposed into a series of sub-systems that represented the core functionality of the system. Each of these sub-systems followed the established development process from conception to embodiment using the information from the design specification and enterprise models as guidance. The final solution utilises an electromechanical programmable motion control system which combines existing industrial servo drive technology with customised transmission components and structural framework elements. These systems have been integrated in an overall design which is relatively simple but provides new levels of safety and reconfiguration which are currently not available with existing training equipment. The inclusion of a series of novel mechanisms allow the provision of aerobic and anaerobic exercise using a single resistance source.

> **Research question 5** - *How can the design and implementation of current exercise interfaces be enhanced to improve usability?*

Software development was decomposed into two aspects: low level control and high level human machine interface. Each of these systems is based upon the structure, behaviour and information illustrated in the enterprise system models. The low level software utilises traditional control concepts and proprietary programming languages to produce the desired exercise actions via the mechanical assembly. The high level interface software was structured and written using industry standard practices to produce a reconfigurable and scalable display which will allow pre-exercise configuration, real time performance adjustment and monitoring and post-exercise analysis and data storage. Facilities have also been provided to incorporate multi-media entertainment and network based communication applications within the exercise system display.

> **Research question 6 -** *What performance capabilities can be achieved using the technologies identified in research question 4?*

A series of validation and reliability experiments were designed to investigate the accuracy and repeatability of the output exercise parameters and performance measurement systems. Statistical analysis of the results of these tests indicated that positional accuracy, static and dynamic torque measurement and velocity and torque control capabilities were comparable with values extracted from existing isokinetic dynamometers and resistance training equipment. Rudimentary user performance tests were also conducted to demonstrate the practical data collection facilities of the modular exercise system. Subject test results indicated a close correlation with normative peak values and general trends established during clinical and academic studies. The operation of the isotonic inertial load and variokinetic exercise programs were demonstrated successfully and shown to produce the desired torque relationships.

8.2 Recommendations for future research

The multi-function modular exercise system developed during this research has demonstrated the potential of an advanced computer controlled resistance source. The operational capabilities of this platform have introduced a number of novel training systems and exercise modes which require further investigation. A number of additional research questions that were created following the completion of this study are discussed in the next sections.

8.2.1 Modification of the mechanical and electromechanical systems

The exercise attachments developed during this initial research were selected to illustrate typical examples of aerobic and anaerobic training devices. In order to demonstrate the potential offered by this multi-function facility, additional attachments must be created and tested. Alternative aerobic systems such as skiing simulators and rowing machines could be integrated with the core resistance machine to provide increased actuation capability which should provide a more realistic training experience. Further design iterations could be conducted to reduce the overall dimensions and infrastructure requirements of the prototype system to improve usability and integration.

8.2.2 Integration of new training concepts into the existing software interface

The reconfigurable and scalable features of the software interface allow new and previously untested stimulus to be implemented and examined without creating specific applications. The effect of entertainment, networked communications and intelligent visual and audio feedback can be investigated by embedding these elements with the user display. The concept of remote training and expert assistance could also be investigated.

8.2.3 Validation tests and state of the art exercise modes

The user performance testing conducting during this research demonstrated the principal operation of the isotonic inertial loading and variokinetic exercise modes. However, additional testing is required to quantify the acceleration experienced during the inertial repetitions in order to prove that the torque adjustment algorithm is producing a representative factoring effect. Detailed experimental trials are also required to investigate the effect of the individual variokinetic exercise parameters. External measurement of the movement velocity achieved during the exercise is required to validate the deviation between the recorded signal versus and the demand velocity.

8.3 Final conclusions

The multi-function modular exercise system developed during this research has utilised existing hardware and software solutions in a novel application domain. The system provides an extensive range of physical training modes including both anaerobic and aerobic exercises to allow specific muscle groups to be targeted with a single resistance unit. A modular design approach was adopted to reduce the complexity of the reconfiguration process and comprehensive mechanical, electromechanical and software based safety systems have been implemented to reduce the occurrence of direct and indirect injuries to the user. A motivational, user centric human machine interface has been developed which is based upon industry standard data collection, storage, analysis and presentation techniques. The prototype system has been shown to produce valid and reliable results during subject testing. Therefore, it is possible that this platform could be developed during future research to create a standardised exercise system for use in the home, in commercial training facilities and in academic and medical research environments.

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Appendices

Appendix A

Product design specification

1. Aesthetics

As identified from the market research products such as this are sold primarily upon its functional capabilities and safety, but also on appearance with respect to current fashion trends.

1.1. The system must be designed to complement existing gym equipment styles whilst helping to depict the technical nature and sophistication of the device.

1.2. Clear and consistent colour coding of moving parts and adjustment features should be made.

1.3. External finishes must be durable, hygienic and safe under continual exposure to the specific environmental conditions (Section 9).

1.4. Internal finishes are to be applied where necessary with a view to minimising excessive manufacturing processes.

1.5. Any relevant safety information or operational displays should be clearly presented and integrated with the product structure with consideration given to good ergonomics. This data should not be impaired during normal operation or be able to be removed by the user.

1.6. The system should present a clean, simple and welcoming aesthetic impression to the client through careful use of shape, colour and texture.

2. Company Constraints

2.1. As part of a research development project there are no direct company constraints although funding time scales must be adhered to.

2.2. A proof of concept prototype with limited reconfiguration is to be manufactured for testing and development of mechanical, electric and software components. This prototype will form the basis for a second unit, which will demonstrate the complete system in a commercially viable product form.

2.3. Further commercial development as expected to be achieved through close partnership with an existing exercise equipment manufacturer.

2.4. As a research device, both systems will be retained by the university, for data collection and experimental testing.

3. Customer

3.1. The system target market is segmented into three broad categories:

1. In-home consumers
2. Commercial gyms and fitness suites
3. Medical and academic facilities

3.2. Product features must be tailored to suit the different customer requirements.

1. In-home users have been shown to base purchasing decisions heavily upon cost, appearance and product advertising. Entertainment and ease of use are essential to maintain interest whilst size is also an important consideration. Data requirements are minimal although may provide a useful competitive advantage.
2. Commercial gyms and fitness suites require a system which is easy to reconfigure and provides a wide range of exercise modalities with minimal space requirements. The inclusion of performance monitoring and exercise prescription systems via a central database is also desirable. Initial purchase cost is a major factor together with system reliability.
3. Medical and academic facilities require high accuracy and repeatability of precisely defined exercise regimes. Reconfiguration for a wide range of users and body positions is desirable. Data collection, storage, analysis and presentation are essential features.

4. Competition

4.1. For this system, the fundamental competitive advantage will be based upon a step improvement in functionality, connectivity and data storage and distribution.

4.2. The aim of this system is to provide a viable replacement for all resistance training equipment with a focus on the direct substitution of commercial selectorised, plate load and dynamometer machines.

4.3. It is envisioned that system reconfiguration features will allow direct competition to in-home, commercialised gym and medical equipment manufacturers.

5. Target Cost

5.1. As a primary issue, costs must be carefully monitored during prototype development although extra expense is likely to be incurred due to the bespoke nature of these initial systems.

5.2. Projected final costs have been broken down according to the market segment, these represent relatively large investments for the in-home user and average expenditure for most commercial gyms. However, the range of functionality on offer far exceeds any product currently available at these price levels. The projected costs for medical and academic institutes represent considerable savings when compared to current devices which retail for approximately £40,000.

1. £800-1000 for in-home applications
2. £4000-6000 for commercial gym applications
3. £10,000-15,000 for medical and academic applications

5.3. Projected cost savings should be documented assuming high volume production capabilities that may be achieved through commercial partnership.

5.4. Costing of post purchase internet based expansion packages, interactive and virtual gaming environments, intelligent training and competition features and any over additional facilities should be investigated and carefully documented with consideration given potential reductions in initial purchase price.

7. Disposal

Currently, the manufacturer is not responsible for the recovery and disposal of this type of product. It is down to the judgement of the customer to decide how the equipment is to be discarded.

6.1 The use of hazardous materials is to be avoided, and in light of future government legislation the use of recyclable materials where no performance or cost penalties are foreseen should be investigated and implemented.

6.2 The system must be easy to disassemble to aid in the removal of electrical and electronic equipment which must be discarded as outlined by governmental policy.

7. Documentation

7.1 System documentation must include the following:

1. Installation instructions
2. Operational instructions
3. Maintenance guide
4. Trouble shooting

5. Test certification and service history
6. Safety issues

8. Ergonomics

8.1. The positioning system must accommodate for differences in body structure between both genders over a range covering the 5th percentile to the 95th percentile as defined in standardised anthropometric data.

8.2. All age ranges should be considered above a minimal datum of 10 years of age. This datum has been set due to potentially damaging physiological developments and the probability of poor form.

8.3. Axial alignment of the joint and resistance system must be maintained to prevent injury.

8.4. Entrance and exit to the system must be as simple as possible with limited intrusion of immoveable obstacles.

8.5. Any displays must provide information which is clearly legible for all users throughout the exercise and should be positioned for maximum comfort ideally in the sagittal plane.

8.6. Both active and passive physical interfaces between human and machine should be designed to maintain comfort and support during exercise.

8.7. Additional user support structures should avoid the compression of contracting muscle groups and avoid positioning the head below the remainder of the body.

8.8. Heat generation and extraction should avoid direct user exposure.

8.9. Noise should be kept to a minimum with an acceptable maximum value of around 65Db.

8.10. General visual impairments caused by the surrounding structure should be minimised.

9. Environment

9.1 Working Environment:

9.1.1 The product will be stored inside.

9.1.2 The unit must be able to fully operate following constant storage for 24 hours a day at temperatures between 0°C and 30°C in relatively high humidity.

9.1.3 Aesthetic appearance and performance should not be affected following constant storage in direct sunlight or under exposure to moisture created during exercise.

9.1.4 Aesthetic appearance and material properties must not degrade under repeated exposure to cleaning products used to maintain system hygiene.

9.1.5 The system must be able to withstand impacts from other exercise equipment and replaceable activation devices.

9.1.6 The system must be able to operate during periods of externally induced vibrations caused by other equipment.

9.2. No fumes or environmentally damaging products should be released during use.

9.3. Power requirements should be based upon a single phase 240v supply.

10. Legal Issues

10.1. The system must carry all relevant safety documentation, warnings and signs.

10.2. All patent issues must be explored to avoid infringement.

10.3. The system must comply with the relevant sections of the following standards;

1. European Standard EN957-1 (1997) Stationary training equipment – General safety requirements.
2. European Standard EN957-2 (1997) Stationary training equipment – Strength training equipment, additional specific safety requirements and test methods.
3. European Standard EN60335-1 (2002) Safety of household and similar electrical appliances – General requirements.
4. British Standard EN60601-1 (1990) Medical electrical equipment – General requirements for safety.

11. Life in Service

11.1. The unit must be able to operate over the maximum range of motion at maximum load for 40 minutes per hour, 14 hours a day and 7 days a week over the entire life in service.

11.2. Predicted life in service has been specified as 10 years (approximately 50,000 operational hours) during which a 100% safety record must be maintained.

12. Product Life Span

12.1. The product life span before the unit is superseded is expected to be around 5-10 years.

13. Maintenance

13.1. Due to the nature of the system a qualified engineer will be required to complete any major repair or maintenance work.

13.2. Acceptable maintenance periods differ according to the precise application;

1. Ideally, In-home systems should require zero maintenance throughout the entire product life span, although a minimal level of serving should be tolerable.
2. An acceptable maintenance schedule for gym and fitness suite systems will involve frequent minor maintenance with major services once or twice a year.
3. Medical and academic institutes may require much higher service intervals to ensure that accuracy and repeatability can be sustained over the product life span.

13.3. The product must be able to provide a high level of functionality under minimal maintenance conditions experienced during periods of neglect, an important issue in in-home and commercial gym environments.

13.4. High frequency, low risk maintenance should be simplified as far as possible to reduce user input.

13.5. The system must be easy to clean in order to maintain hygiene.

14. Manufacture

14.1. All manufacturing processes and procedures for construction of the prototypes will be undertaken by university personnel with additional assistance from external contractors.

14.2. Consideration should be given to potential large volume manufacturing requirements a focus upon minimising additional tooling or production techniques and overall ease of assembly.

14.3. The use of standardised components where possible is to be encouraged.

15. Patents

15.1. Existing Patents identified during research should by noted and any breach avoided.

16. Performance

16.1. The prototype system must provide sufficient performance characteristics for all types of user and match or exceed that offered by competitive equipment.

16.2. Initially the system will be configured for exercising the elbow and knee joints in order to demonstrate the range of performance requirements, although consideration should be given to all muscle groups. These values are to be collected from existing data and any additional testing that may be required

16.3. The following modes of exercise must be incorporated;

1. Isometric
2. Isotonic (concentric and eccentric)
3. Isokinetic (concentric and eccentric)
4. Variokinetic (concentric and eccentric)
5. Aerobic

16.4. The system must exceed the range of motion of the muscle groups being exercised.

16.5. Internal losses should be minimised in order to maximise data accuracy.

16.6. Careful consideration should be given to the use of rotational resistance motions for the approximation of linear exercises.

16.7. A full database of maximum and minimum performance parameters and profiles is to be assembled for specification of the commercial system.

17. Quality and Reliability

17.1. The customer must view the system as reliable, well constructed and safe.

17.2. Quality Standard ISO 9001 should be utilised where possible.

18. Quantities

18.1. Although the system will only initially be produced as a proof of concept, predicted production quantities for commercial systems are around 5000 units per annum.

19. Safety

19.1. The safety standards outline in section 10. 'legal issues' must be adhered to.

19.2. The design should include both software and hardware fail-safe mechanisms in case of failure during operation with the provision of suitable deactivation procedures for each mode of exercise.

19.3. Provision should be made to resist reaction forces created during exercise through the use of support devices such as seatbelts.

19.4. Excessive shielding should be avoided to prevent restricted ventilation of the user, additional trapping hazards and reduced visibility.

20. Size

20.1. The system must fit within a maximum envelope of 2m x 2m x 2m, although any reductions below this value while maintaining stability would be beneficial.

20.2. Where multiple units are in operation, tight positioned is desirable in order to conserve space.

20.3. System weight must be sufficient to provide stability during all modes of exercise. It is envisioned that the main resistance unit, once installed will remain in a fixed location. Therefore, weight will only be an important factor during initial installation. Any additional units that may be developed are luckily to be interchangeable and thus weight should be specified to ease manoeuvrability.

21. Testing

21.1. The prototype performance characteristics must be thoroughly investigated and documented using a series of detailed test procedures to be determined during the development process.

21.2. Isolated testing should be conducted on the mechanical, electrical and software systems together with total system analysis.

21.3. Testing must be carried out to ensure correct operation and specification of safety systems and failure levels.

22. Timescales

22.1. Mechanical construction of the initial prototype is to be completed by the end of the first year of research. This equipment must be supported by elementary software and electric systems for proof of concept evaluation.

22.2. During the second year, systems integration and development should be continued with a view to the production of a full functional secondary prototype for the demonstration of commercial features, system functionality and design ideas.

22.3. Year three has been assigned to the collection and analysis of test data for determining precise training responses using the proposed system and original contributions to academic and medical knowledge.

23. Materials

23.1. The material must be comply with all performance requirements (see section 9 'performance').

23.2. The material must be of suitable cost such that it meets the requirements specified in section 5 'cost'.

23.3. The materials must be capable of operating in the specified environment. (See section 9 'environment').

23.4. The material must be capable of meeting the weight limits detailed in section 20 'size'.

23.5. The material must meet all relevant standards specified in section 10. 'legal issues'.

Appendix B

CIMOSA enterprise models

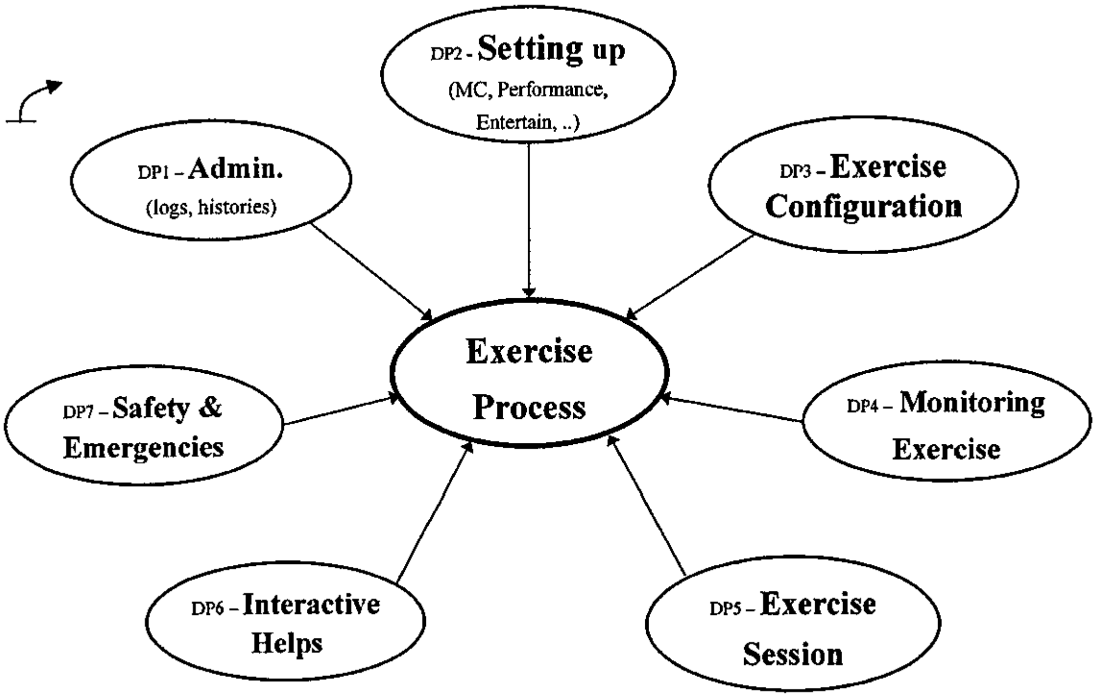

Figure B.1: Modular exercise system CIMOSA Context diagram.

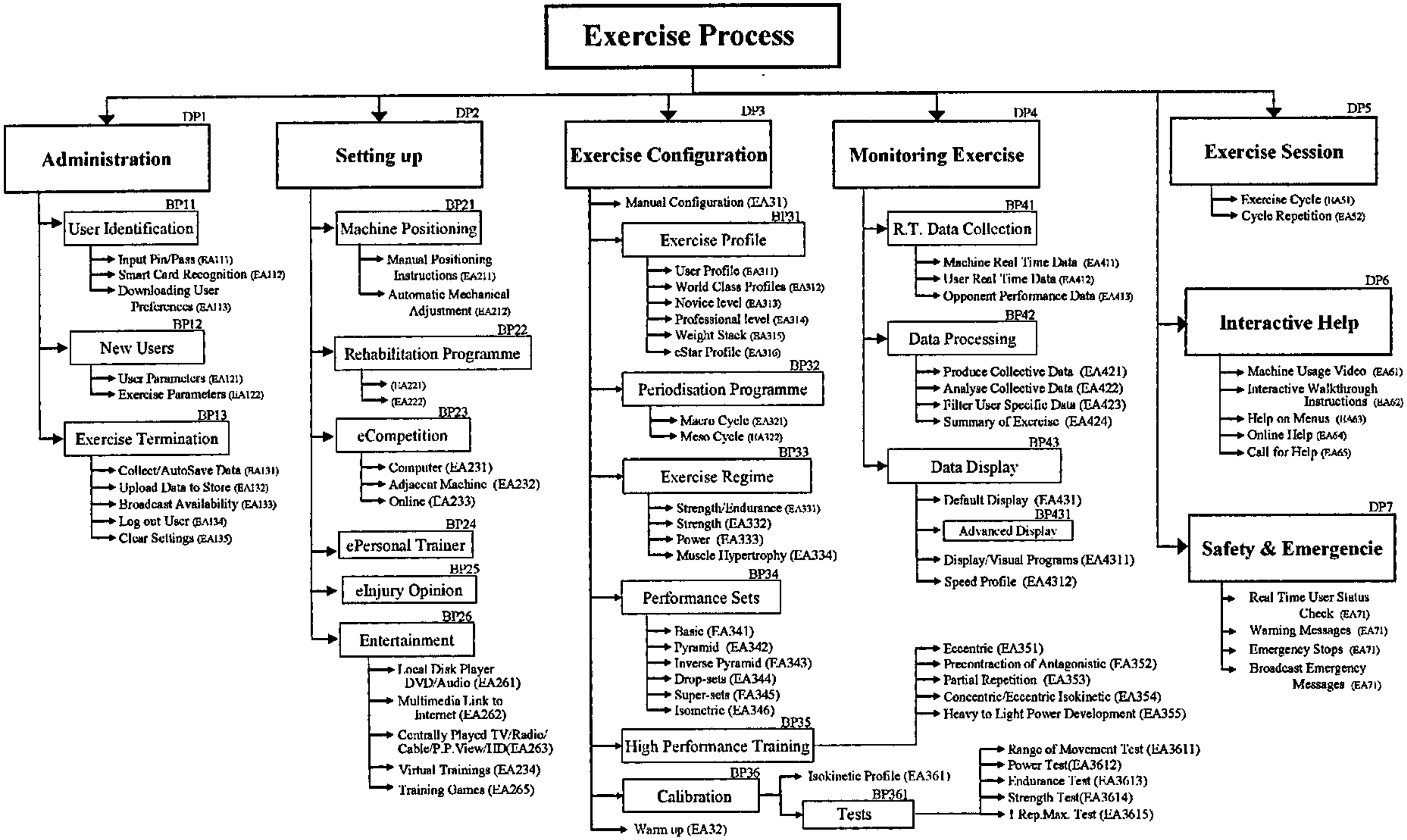

Figure B.2: Modular exercise system CIMOSA structure diagram.

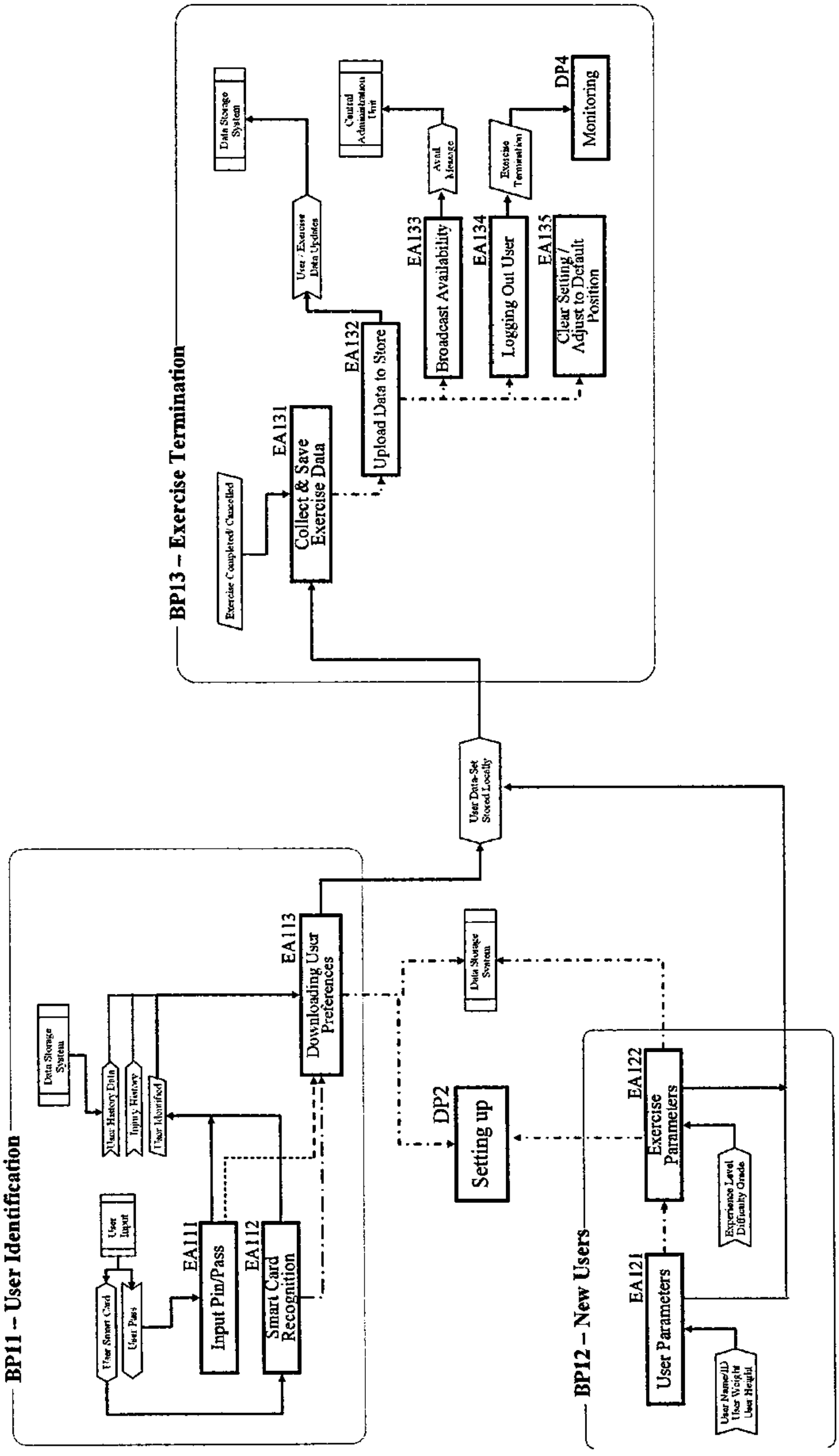

Figure B.3: Modular exercise system CIMOSA activity diagram.

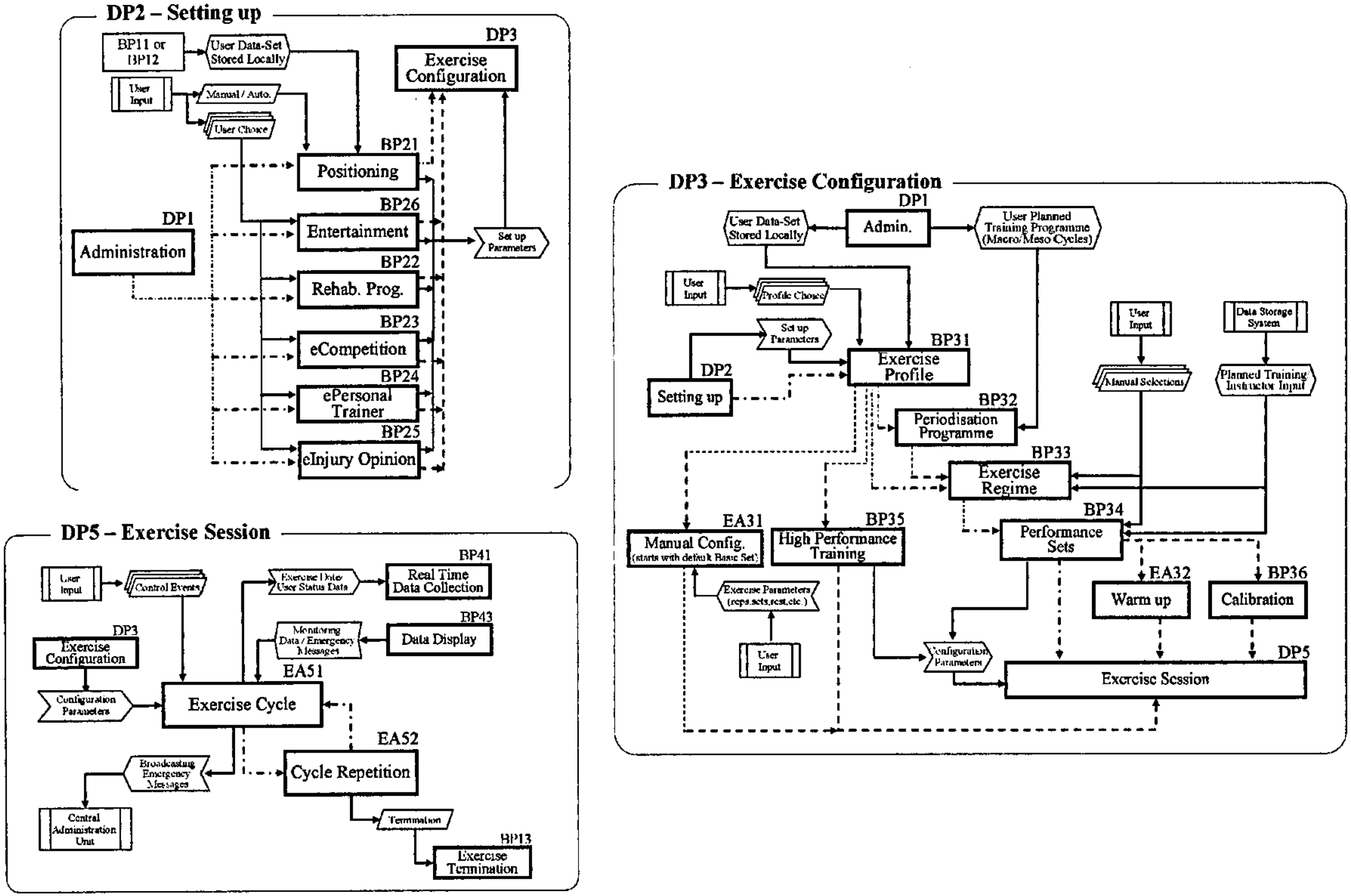

Figure B.4: Modular exercise system CIMOSA activity diagram.

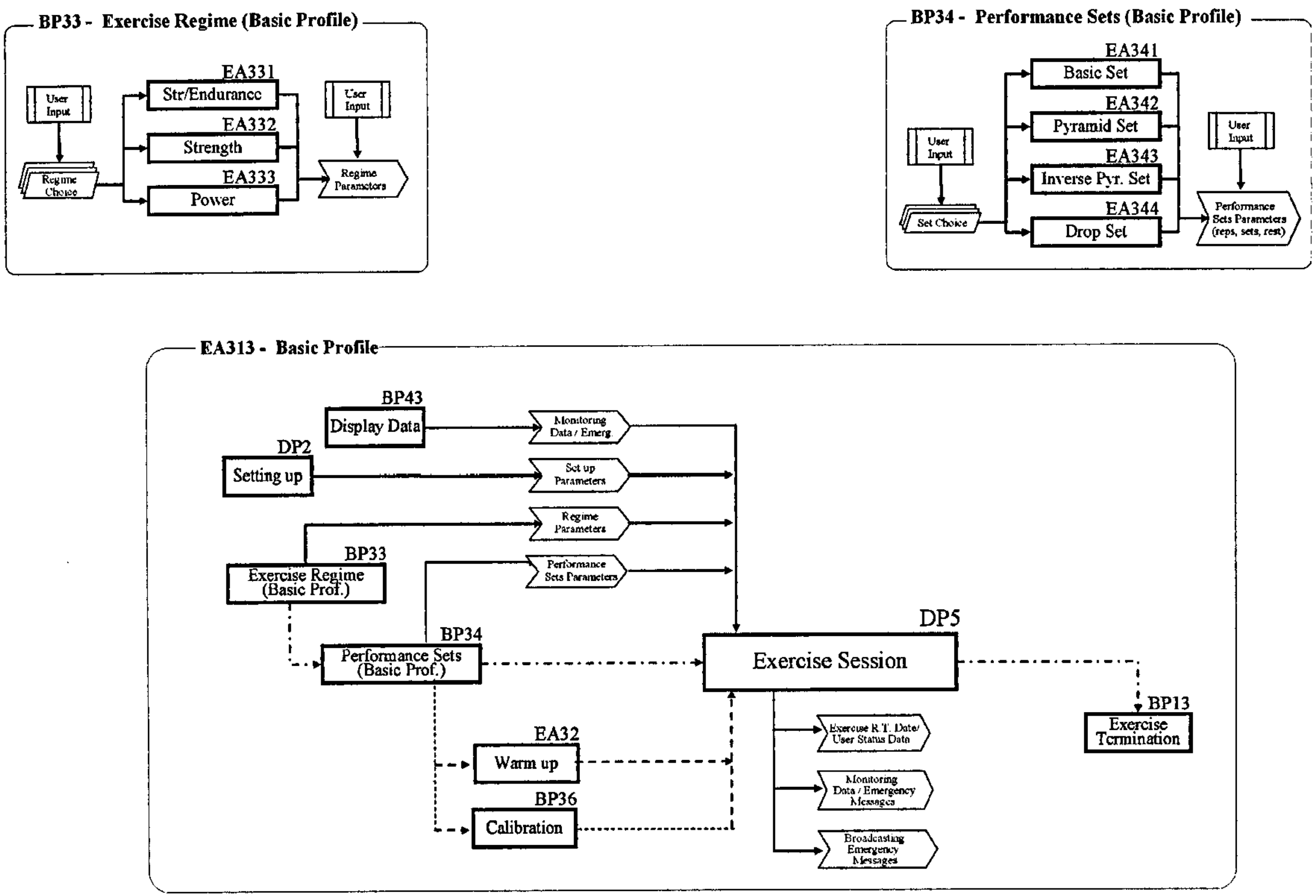

Figure B.5: Modular exercise system CIMOSA activity diagram.

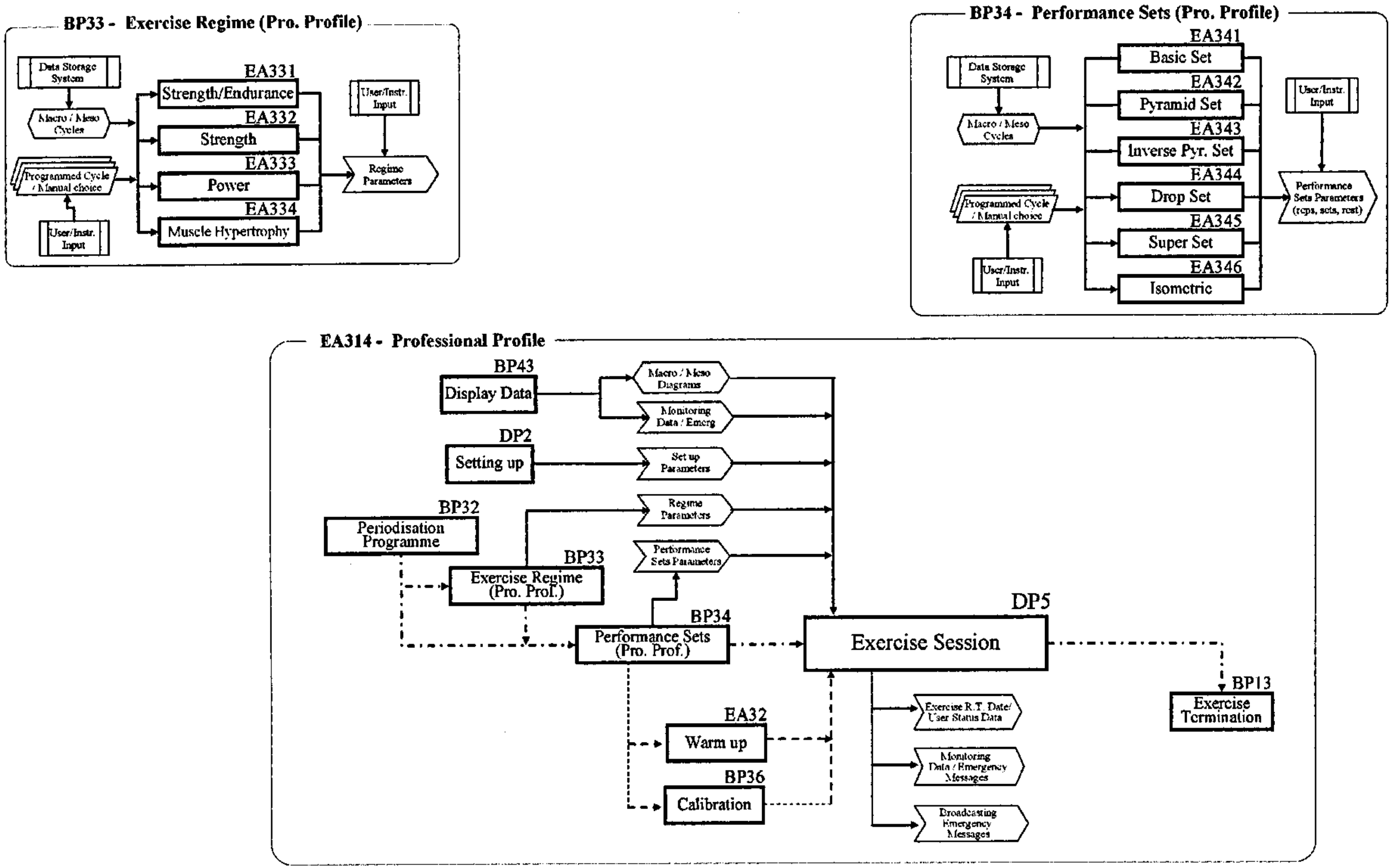

Figure B.6: Modular exercise system CIMOSA activity Diagram.

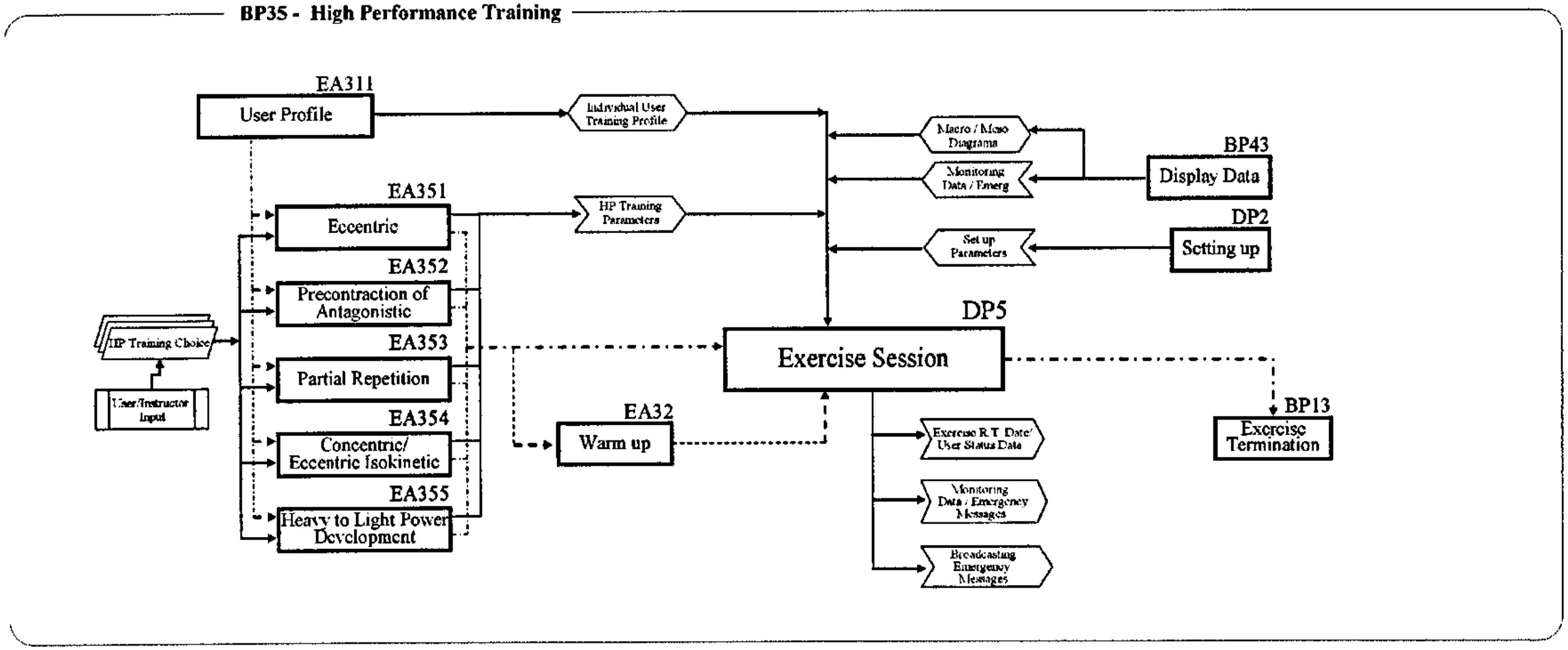

Figure B.7: Modular exercise system CIMOSA activity diagram.