

AN ERGONOMIC ANALYSIS OF COMMERCIALY AVAILABLE EXERCISE  
EQUIPMENT : IMPLICATIONS FOR RESISTANCE TRAINING AND  
CLINICAL REHABILITATION.

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THESIS

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## ABSTRACT

This study examined the often contrived advertising claims of the manufacturers of variable resistance isotonic machinery. Specifically, the study sought to ascertain whether certain equipment was compatible with musculo-skeletal and perceptual needs and limitations of the human user: that is, to determine whether presently installed eccentric cams, which provide the variable resistance, matched the users force curves.

The format of this research was in the ergonomic tradition in which empirical research is not necessarily the primary avenue. Consequently the inter-disciplinary nature of ergonomics required small-scale laboratory- simulation experiments to be conducted in a diverse range of disciplines such as physiology, psychology and biomechanics.

It was found that on all five pieces of variable resistance machinery analysed, a mismatch between the force curves and the eccentric cams exist. The cams were redesigned accordingly. The metabolic cost of performing fixed-rate isoinertial lifts was moderate. The psychophysical analysis revealed that perceptual responses indicated that the work was classified as 'light' and only at 30% stress levels do local cues begin to dominate.

Based on these findings it was concluded that manufacturers advertising claims in the instances analyzed were not well-founded and that variable resistance isotonic machinery should only be used to develop muscular strength and

endurance, and do not effectively serve as weight-loss devices.

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## CHAPTER ONE

### INTRODUCTION

Within the domain of ergonomics, the causes, frequency, severity and cost of manual materials handling (MMH) injuries has been well documented (Chaffin and Andersson, 1984; Nicholson, 1985). Scott and Walraven (1990) stress the importance of matching worker capabilities to actual task demands because any mismatch will increase the likelihood of injury incidence. Steps must, therefore, be implemented to reduce injury incidence by considering the human operator and his/her characteristics. According to Grandjean (1988), this implies that rigorous worker selection processes be undertaken. Ayoub *et al.* (1983) emphasise the importance of defining the capacity limits of individuals and of operating within them. In identifying individual capacities for safe lifting, researchers have used models which incorporate epidemiological data, muscular strength and endurance, biomechanical load, physiological capacity and psychophysical capacity (Ayoub *et al.*, 1983; Snook, 1978).

In a recent report the American College of Sports Medicine (ACSM, 1990), revised and updated their recommendations for exercise in healthy adults. A major difference from their earlier (1978) guidelines is the expansion of their recommendations to include exercise for muscular strength and endurance. Thus, resistance training is believed to be one of the cornerstones of a well-rounded

development programme.

Kisner and Colby (1990) emphasise that in a rehabilitation or clinical setting, the therapeutic use of resistance training in an exercise regimen, whether applied manually or mechanically, is an integral part of a patient's plan of care when the ultimate goal is to improve strength, endurance and overall physical condition.

Thus, the earlier emphasis, in which resistance training was seen as the domain solely of select athletes wishing to enhance their prowess, has now expanded to incorporate its routine use in a wide variety of circumstances including injury prevention and rehabilitation, weight control, physique and postural improvement, and the work-hardening of manual materials handlers in industry (Ayoub and Mital, 1989; DiNubile, 1991).

The development of commercial health and fitness centres in South Africa, and the need for testing and training in an industrial and commercial setting, has resulted in an increased demand for, and supply of, resistance training equipment. However, the often spurious advertising claims of the manufacturers of this equipment have gone largely unchallenged. Whether the design allows a piece of equipment to be used as originally intended by the designer is problematic.

The problem at issue is whether equipment design is compatible with the musculo-skeletal and perceptual needs and limitations of the human user. For example, muscles contract at differing percentages of their maxima through the range of

motion against a constant resistance. Typically the torque development capacity of a joint is greatest at its mid-range and reduces either side of the mid-range as the muscle's own lever arm distances decrease. The weight moved during isotonic efforts is therefore limited by the inherent "weak-point" on the strength curve of the muscle. Here a biophysical constraint is evident, quite apart from psychological factors that might impinge on the situation.

Therefore, when a muscle contracts dynamically against isoinertial resistance, the tension produced in the muscle increases or decreases as the muscle lengthens or shortens through the range. At certain points in the range, the muscle-bone lever works more favourably than at others, so that the constant load in isoinertial situations exerts a variable stress on the muscle(s) moving that load. Despite the fact of a constant external load, so called "isotonic" effort is limited by the inability to impose maximal tension and work demands at all points on a muscle through its range.

The development of eccentric cams was a design-attempt to vary the resistance experienced by the working muscle through its range of motion. The cam serves as an efficient fulcrum when the musculo-skeletal lever is inefficient and vice-versa. The desired effect is to maintain constant tension in the working muscle(s) at all points through the range of motion.

Harmon (1983) has argued that the claim that variable resistance training modes accommodate muscular force capabilities may be unfounded. Although these machines

undoubtedly provide a more compact, convenient and safer form of external loading than do barbells and dumbbells, their existence has raised the inevitable question of whether they are superior with respect to strength development (Hay et al., 1982). Further, there is some doubt as to whether muscular force capabilities are truly accommodated by variable resistance machines, and recent research has failed to show significant strength gains in variable resistance over constant resistance exercise (Manning et al., 1990). The use of eccentric cams on variable resistance machines in South Africa has not hitherto been questioned or the cam shapes themselves validated.

#### **STATEMENT OF THE PROBLEM**

Ergonomics is inter-disciplinary in nature, drawing on knowledge from human psychology, physiology, anthropology, biomechanics and industrial design and engineering (Fraser, 1989). This falls within the holistic conceptual framework proposed by Charteris et al. (1976) whereby human movement is studied from a psycho-socio-physio-anatomico-aesthetic perspective.

Given the interdisciplinary nature of ergonomics, an ergonomic intervention attempts to optimise situations, usually involving a man-machine interface, and drawing from a range of disciplines. Man-machine interfaces constitute problems that are never completely solved because different users than those for whom the equipment was designed, often use such equipment, in different ways than were originally

intended by the designer.

Empirical research was not the thrust of this project although, when appropriate, small-scale laboratory-simulation experiments were deemed necessary to obtain some idea of response-ranges and mean values which are arguably representative of assumed/intended user group(s). Therefore the format of the research undertaken in this study is in the tradition of ergonomics, which is typically in the nature of survey, problem identification, re-design, and trial and error-elimination, i.e. which makes use of, but does not rely solely upon empirical research strategy.

In the present study six items of South African-manufactured exercise equipment designed to effect optimal strength gains were evaluated, the ultimate goal being to formulate generalised statements and recommendations with respect to musculo-skeletal exertions on this type of equipment, with implications for injury rehabilitation and prevention, sports training and occupational safety.

According to Bandy et al. (1990), an understanding of all adaptations occurring in response to resistance training provides a fundamental basis upon which appropriate exercise training programmes can be developed. However, Charteris et al. (1976) caution that not all four domains of an holistic model need necessarily be treated in every situation under investigation. Clearly logic, and the sanity of the investigator(s), dictates that the answering of a problem in, as opposed to around, human movement, while it may involve biophysical, physiological, and psycho-social variables, will

be attempted in terms of the most critical factors pertaining in the circumstances. Thus the primary focus of the present study involved recording the isometric torque maxima of subjects performing on the equipment in order to specify the typical strength curve. Points at which there is a mismatch between present cam design and determined force curve constitute the locus, and help identify the extent, of flaws in the equipment design.

#### **DELIMITATIONS**

Mixed-sex groups of healthy young adults were used to determine responses since it was felt that both sexes utilise the equipment investigated in this study.

In order to obtain as subjects individuals who had some experience of resistance training, yet who at the same time were in varying states of physical condition, recourse was made to the use of students majoring in Human Movement Studies. Subjects representing as wide a range as possible, with respect to body size and physical work capacity, were used.

In order to ensure that maximal isometric contractions were indeed effected, each subject was required to make three isometric efforts at each of the four positions in the range of the musculo-skeletal lever system involved; the highest force recorded being taken as the representative maximal value.

This analysis was delimited to a range of equipment incorporating demands on regions of the axial and

appendicular skeletons, as follows:

1. Shoulder complex ..... 'Pec-Fly' unit
2. Knee joint ..... Knee Extension unit
3. Shoulder complex ..... 'Pullover' unit
4. Trunk ..... 'Abdominal' unit
5. Hip complex ..... 'Abductor' unit
6. General ..... 'Under-Over' Pulley unit

#### **LIMITATIONS**

Only 10 subjects (5 males and 5 females) were used in each of several laboratory simulation experiments. The number of subjects used was not sufficiently large to generate conclusive statements with respect to trend and factor analysis, but since this was not the goal it was felt that small, representative samples would suffice to demonstrate weaknesses inherent in the design of the equipment under investigation.

Maximal isometric contractions were only tested at four evenly-spaced points through the range of motion for each exercise on each piece of machinery. Torque curves and re-designed cam radii were derived from these data. More accurate torque curves and cam designs could have been determined by performing the isometric contractions at more than four points during the range, but, again the data provided were sufficient to identify design flaws and to effect required design improvements.

No habituation period was provided to familiarise subjects with the exercises executed on each piece of

machinery and with the relevant testing conditions and equipment. This may have added artifact to the results due to unaccounted-for anxiety, or discomfort on the part of the subjects, placing unaccounted strain on the selection criterion (subjects familiar with resistive exercise in general, if not with the specific unit presented).

During maximal isometric contractions, it was not known whether a subject ever exerted the maximum force possible, as inhibiting factors such as discomfort and pain during the isometric contractions were unaccounted for.

It was not logistically feasible to control the amount of activity carried out by the subjects prior to any of the laboratory experiments. Therefore, certain individuals may have been fatigued prior to the testing sessions and consequently may not have performed maximally as a result, thereby affecting the results.

## CHAPTER 2

### REVIEW OF RELATED LITERATURE

#### INTRODUCTION

Resistance training has experienced a significant increase in popularity in the last decade. It had previously been used primarily by select athletes wishing to develop their prowess.

However, its role has now expanded to routine use in a wide variety of circumstances, including injury rehabilitation and prevention, weight control, and physique and postural improvement (DiNubile, 1991). Human strength has also been applied for predicting the manual lifting capability of individuals in industry (Ayoub and Mital, 1989), and it has been found that an improvement of an individual's working capacity can be made possible through a physical training programme.

With the advent of commercial health and fitness centres in South Africa, the use of "cosmetic" exercise resistance training equipment has increased remarkably, yet few have ever questioned the use of the equipment and whether the design allows it to be used in ways that it was originally intended by the designer: whether, in short, the machine or equipment is designed to be used within the limitations of man's musculo-skeletal, physiological and psychological limitations.

Man's morphology is pre-determined by his genetic structure and is therefore relatively unchangeable within a

lifetime. However, the tasks, the equipment and the working environment are created and developed by man, and therefore are adjustable. Given the interdisciplinary nature of ergonomics, an ergonomic intervention attempts to optimise situations, usually involving a man-machine interface, drawing from a range of disciplines as diverse as engineering and social psychology.

According to Ayoub and Mital (1989), one aim of the ergonomist is to reduce the stress imposed on the worker sufficiently to minimise musculo-skeletal and/or physiological strain. In essence, working conditions need to be adapted to the psychophysical nature of man. In other words, the demands of work need to be fitted to the efficiency of man in order to reduce stress (Grandjean, 1980).

A number of researchers have studied the metabolic cost of performing resistive type exercises (Collins et al., 1991; Katch et al., 1985; Peterson, 1976), while other authors have attempted to analyze the biomechanical aspects of this form of training (Lander et al., 1984). Certain authors have produced human strength curves (Kulig et al., 1984), and a large literature exists comparing the different resistance training modalities (Coleman, 1977; Fleck and Schutt, 1985; Katch and Drumm, 1986; Kosmahl et al., 1989; Manning et al., 1990; Smith and Melton, 1981). In industrial settings, psychophysical criteria have been employed in an attempt to determine maximal acceptable weight of lift (Gamberale et al., 1987; Garg and Saxena, 1980, Nicholson and Legg, 1986; NIOSH, 1981;

Snook, 1985), and whether dynamic strength measures are adequate predictors of performance (Dales et al., 1986; Kroemer, 1983; Stevenson et al., 1989).

However, discrepancies are present in some results reported in the literature, which may be due in part to inconsistencies in methodologies employed, and in part to the large number of factors collectively involved in physical exertion during resistance exercise. According to Bandy et al. (1990), an understanding of all adaptations occurring in resistive training provides a fundamental basis for which appropriate exercise training programmes can be developed.

To date it appears that no holistic study drawing on a number of disciplines - culminating in an holistic interdisciplinary study on isoinertial resistance training equipment has been conducted in South Africa. Yet, it seems that there is a need to understand all possible responses to resistance training before design alterations are effected in isoinertial resistance equipment and associated training regimen.

## **ERGONOMICS**

The science of ergonomics is little more than 40 years old, its founders being a group of British scientists, who had been working for the Armed Services on various projects concerned with the efficiency of the fighting man in World War II (Pheasant, 1991). Included in the group were anatomists,

physiologists, psychologists and engineers. These scientists believed that a multi-disciplinary scientific approach to the study of working efficiency could be equally relevant to industry under peacetime conditions.

Ergonomics is defined in a number of ways, the simplest being: "Ergonomics is the study of human work" (Pheasant, 1991). However, work requires some classification. In a narrow sense work refers to the things we do for economic gain - that is to earn a living. In the broader sense "work" may refer to almost any kind of human activity which involves purpose or effort (Pheasant, 1991). According to this author, the science of ergonomics deals with work in the broader sense, although work in the limited meaning has been central to its development. Work generally involves the use of machines and tools, and ergonomics is therefore also concerned with the effects of tool and machine designs.

Pheasant (1991) explains that in some ways it makes more sense to define ergonomics in terms of its role in the design process, as this will tend to reflect more accurately what the practising ergonomist actually does. Consequently Pheasant (1991) defines ergonomics as "the application of scientific information concerning human beings to the design of objects, systems, and environments for human use."

Murrell (1969) defined ergonomics as the scientific study of the relationship between man and his working environment (Fraser, 1989). This definition was expanded upon by Fraser,

who saw that ergonomics can be considered as the study of the anatomical, physiological and psychological aspects of workers in their working environments.

Fraser (1989) explained that ergonomics is interdisciplinary in origin, taking its knowledge from human psychology, physiology, anthropology, biomechanics, and industrial design and engineering; each in its own way dedicated to improving the lot of the worker in the workplace and the manner in which the tasks are performed. The interdisciplinary field of ergonomics has manifested itself in the optimisation of human performance within the working environment, with particular emphasis on comfort, efficiency, safety and reliability pertaining to the workplace. Recognition of sub-optimal performance conditions is essential in order to alleviate such problems as injuries, compensation costs, absenteeism, high turnover and poor productivity that prevail in industries world-wide. In other words, the objectives of ergonomics are two-fold: firstly to enhance the effectiveness with which work and other human activities are carried out, and secondly, to maintain or enhance certain desirable human values such as health, safety and satisfaction in the process (McCormick and Sanders, 1982).

### **Ergonomics and Design**

What is meant when a product is ergonomically designed? In everyday use, the label is usually applied in an evaluative

sense, to indicate various aspects of application for purpose such as functional efficiency, ease of use, etc. (Pheasant, 1991). If a product (environment or system) is intended for human use, then its design should be based on the characteristics of its human users (Pheasant, 1986). This is termed the user-centred approach to design (Pheasant, 1991). This author further says that ergonomics provides the scientific foundation for a user-centred approach in terms of both methodology and research techniques and a steadily growing body of descriptive data concerning the human user, and concerning design solutions which have been satisfactory, or have caused problems in the past. According to Pheasant (1991), the user-centred design has a number of characteristic features:

- (i) It is generally empirical. That is, it is based upon direct observation of the way that people are and the things that they do, rather than being formed from "grand theories".
- (ii) The empirical user-centred approach to design is generally cyclic. It is often based upon an initial task analysis: that is an investigation which sets out to provide an operational description of the actions which the user performs in order to do the job at hand, with the product concerned. This may be done by means of "user-trials", in which a representative sample of users tests an existing product, or a mock-up of a new one. The results

of such investigations suggest modification to the design. These are then tested in further trials, and the cycle repeats itself.

(iii) Ergonomics is concerned with finding the best possible match for the greatest number of people, by adapting the product to fit the user, rather than vice-versa. Much of the scientific basis of ergonomics is thus concerned with defining the limits of human ability and human diversity.

According to Pheasant (1991), if an object is intended for human use, it must necessarily be used for some purpose. This purpose can, broadly speaking, be called work (Pheasant, 1991).

In the working world a person of necessity is a component of many systems. A prevalent concept in ergonomics, according to Fraser (1989), is that operators or users and the machines they operate cannot be considered as individual entities. The consideration of a person as a component of a system was forced upon engineers, designers and planners by a developing technology which failed to recognise not only human limitations and capabilities as part of a combined operation in a technological environment, but also human attributes and assets. Consequently the concept of a person-machine system was conceived, a person-machine system being defined as an aggregate of people and machines operating as a unit to perform a function (Fraser, 1989).

A person-machine system can be defined as an aggregate of one or more human beings and one or more physical components interacting to bring about, from given input, some desired output (McCormick and Sanders, 1982). It must be pointed out that the word "machine" should be considered to consist of virtually any type of physical object, device, piece of equipment or facility that people can manipulate or use in order to carry out some activity that is directed toward attaining some desired purpose, or in performing some function. Thus, ergonomics is also concerned with the design of working systems in which human beings interact with machines. These, according to Pheasant (1991), are man-machine interactions.

Manual Materials Handling (MMH) is considered by Ayoub and Mital (1989) to be a system consisting of three main components: (1) worker; (2) tasks; and (3) environment. Any mismatch among these three components will lead to an ineffectual system which must be tolerated by the human component of the system, often at great cost, suffering and pain, if the system is to remain operational. In the MMH system, the goal is to select a workload that does not lead to excessive fatigue or injury. If the workload does exceed a critical level, it will elicit responses that will be unsafe and lead to excessive fatigue or injury. These responses are adjusted by either the worker or the designer to avoid excessive fatigue or injury.

Within a MMH system the inputs include (1) job factors such as frequency and distance moved (2) personal factors such as physical fitness, age, sex, stature and strength, and (3) environmental conditions such as temperature, humidity and noise. There are also two different types of MMH system output. One involves production output, such as productivity and quality of work, and the other involves human output such as physiological responses of the operator, or biomechanical stresses to musculo-skeletal systems. These outputs can be quantified by various technologies. For example, the physiological outputs can be measured in terms of heart rate or oxygen uptake under experimental or in situ conditions.

#### **Human Limitations**

Over and above any stress imposed from the exterior, intrinsic human constraints exist within a system since a person is a living being with biological limitations which are relatively insusceptible to modification. These have been clarified comprehensively, but not exclusively, by Fraser (1989) as:

1. Physiological - Limitations in power, strength, endurance and capacity to maintain homeostasis under adverse conditions.
2. Psychological - Limitations in learning capacities, skills, performance ability, tolerance of adverse conditions, and motivation.

3. Anthropometric - Limitations derived from a fixed morphology, tissue structure, size and shape of work envelope, and postural requirements.
4. Nutritional - Limitations occasioned by need for maintenance of appropriate food and water intake and requirements for elimination.
5. Clinical - Limitations occasioned by a person's state of health, presence of disease and accompaniments of ageing.

These various factors combine in diverse ways to affect the nature of the human response and modify the effective system. Human limitations arise largely out of the nature of human structure and function. Inherent in this structure are limitations in strength and power which are normally far exceeded by appropriate machines (Fraser, 1989), but which can be improved upon through the correct stimulation and training.

People have certain other capacities that assist them in their tasks. They are both mobile and dexterous, in that they can move of their own free will and can manipulate objects. Each of these capacities is limited as people are neither so mobile nor so dexterous as special purpose machines; but combined with other attributes, these capacities are of great value. People are also capable of a limited amount of self maintenance and self-repair, although readily susceptible to damage.

## **Mechanical Limitations**

Just as there are constraints that affect the human portion of the person-machine system, there are also factors that constrain the mechanical component. Fraser (1989) notes that these constraints, in a sense, are analogous to the human constraints, with, however, one major difference. Whereas human constraints are inherent, inescapable, and not significantly susceptible to modification, mechanical constraints exist in the system because they were placed therein wittingly or unwittingly by the system designer and are therefore open to modification. Fraser (1989) clarifies them as constraints arising out of:

1. Unsuitability of design - a machine or device can only do what it is designed to do. If the design is inadequate then the function will be imperfect.
2. Unsuitability of materials - the materials selected for the structure may be inappropriate to the purpose.
3. Unsuitability of construction - despite adequacy of design and choice of materials, the construction may be unsatisfactory.

Fraser (1989) cautions that if any combination of these is at fault the effectiveness of the system will be compromised. This compromise may be manifest in system function, in its direct effect on the person, in the environment, or in any

combination of these, but in the long term the compromise will affect human function and human capacity.

### **Ergonomics in Rehabilitation**

Mital and Karwowski (1988) point out that historically, ergonomics has aimed at establishing work capacities of healthy individuals and it is in this context that the overall objective of ergonomics has been defined: that of fitting the task to the worker. These authors suggest that very little attention, however, has been paid to the problems of disabled or injured persons. It appears that in the quest for improving the quality of life and working conditions for the masses, a rather substantial part of the population has been overlooked: namely those already injured or disabled. Mital and Karwowski (1988) state that the preponderance of studies dealing with the capabilities and limitations of healthy individuals, published in the literature, underlies this fact. Just as ergonomics is inter-disciplinary in nature, so too is rehabilitation, and perhaps more so. Not only that, but rehabilitating disabled individuals is a global priority for individuals from many diverse disciplines. Although not always apparent, the application of ergonomic principles to remove incompatibility in the human-machine environment (Karwowski et al., 1988), by matching human capabilities and job requirements, is critical to long range success of all efforts aimed at disability prevention and vocational rehabilitation.

Within the domain of ergonomics, the causes, frequency, severity and cost of manual materials handling (MMH) injuries have been well recorded in the literature (Chaffin and Andersson, 1984; Liles et al., 1984; David, 1985; Metzler, 1985; Nicholson, 1985). Garg et al. (1983) state that an estimated 30% of all the total workforce is exposed to hazardous manual materials handling tasks, with over-exertion accounting for 27% of all compensable injury and illness. Some 110 million people suffer from non-fatal musculo-skeletal injuries, of which probably 50% could have been prevented with properly designed intervention programmes (Ferrara and Nordin, 1987). According to NIOSH (1981), musculo-skeletal disorders rank first among disease groups in both frequency and effect.

It appears obvious that in an industrially developing country with a large unskilled labour force, there will be a large component of manual labour. Musculo-skeletal injuries should therefore be much higher, per capita, in South Africa, a developing country with far less mechanisation than the U.S.A. or Europe. Scott and Walraven (1990) stressed the importance of matching worker capabilities to actual task demands because any mismatch will increase the likelihood of injury incidence. Steps therefore need to be implemented to reduce injury incidence by considering the human operator and all characteristics, be they morphological, physiological or psychological. This implies that intense, rigorous worker

selection processes be undertaken, or tasks modified to 'fit' the worker in a cost-effective manner (Grandjean, 1988).

If a worker's physical attributes (e.g. strength, endurance, size) are not sufficient to meet the demands of the task, then exertion-related injuries of various types are more likely to occur. In order to reduce the severity of any injury, it is essential to define the capacity limits of individuals, and to operate within them (Ayoub et al., 1983; Nicholson and Legg, 1986). In this way, by matching the capability of the worker with the requirements of the task, or by designing such tasks on the basis of the capabilities of a certain population group, the risk and severity of manual handling over-exertion injuries is decreased (Chaffin et al., 1978; Garg and Saxena, 1980; Yates et al., 1980; Mital, 1984a).

According to Ayoub et al. (1983) there are two basic determinants as to whether or not a MMH task is injurious to the operator:

1. The occupational requirements, which refer to task requirements such as the mass of the lift for a given frequency and duration, with certain container configurations.
2. The particular capabilities of the operator, in this instance lifting ability, as based on physiological, biomechanical, and psycho-physical criteria (NIOSH, 1981; Ayoub et al., 1983).

In industry, a multi-disciplinary approach to the prevention of musculo-skeletal injuries is required, along with rehabilitation of the injured person (Nordin, 1987). Prevention of injury is a cost effective tool, and as such, employers have a responsibility and the opportunity to encourage their employees to take better care of themselves. Careful pre-employment screening and selection of the workers for jobs entailing MMH is one method of alleviating the risk of back pain (Chaffin et al., 1983) and other work-related injuries. The basis for developing selection standards is to match the physical capabilities (morphology, strength and endurance) of the potential worker population with the actual task demands, in order to reduce the risk and severity of over-exertion injuries (Ayoub et al., 1983; Mital, 1984a; Nicholson and Legg, 1986). Pre-employment screening methods involving heavy work loads include clinical and cardiovascular fitness tests, height, weight and strength tests (Norman et al., 1983).

#### **RESISTANCE TRAINING**

Muscular strength, traditionally developed via the technique of progressive or resistance training, has experienced a significant increase in popularity in the past decade. The technique has long been used primarily by select athletes to improve muscle strength and size. Its role has now expanded to routine use in a wide variety of circumstances,

including injury rehabilitation and prevention, weight control, osteoporosis prevention and treatment, and physique and postural improvement (DiNubile, 1991). Human strength has also been applied for predicting the manual lifting capability of individuals in industry (Ayoub and Mital, 1989). Chaffin and Park (1973) and Chaffin (1975) studied human isometric strength to determine the potential relation to the incidence of low back pain. These results disclosed that low back pain incidence rates sharply increased for those workers who do not have adequate isometric strength to perform lifting tasks. Ayoub and Mital (1989) and Genaidy *et al.*, (1989) found that an improvement of an individual's working capacity can be made possible through a physical training programme.

The American College of Sports Medicine (ACSM) has recently revised and updated their recommendations for exercise in healthy adults (ACSM, 1990). A major difference from the earlier (1978) guidelines is the expansion of their recommendations to include exercise for muscular strength and endurance. The ACSM describe physical work capacity as comprising a variety of characteristics included in the broad categories of cardio-respiratory conditioning, body composition, muscular strength and endurance, and flexibility. Thus, resistance training is believed to be one of the cornerstones of a well-rounded developmental programme. Kisner and Colby (1990) further emphasise that in a well-organised clinical setting, the therapeutic use of resistance

in an exercise programme, whether applied manually or mechanically, is an integral part of a patient's plan of care when the ultimate goal is to improve strength, endurance, and overall physical function.

As a consequence of this increase in the popularity of resistance training, a billion-dollar industry has resulted with significant economic implications for those companies manufacturing equipment for fitness centre owners and for therapists. Further, there is a wide variety of potential resistance training programmes, methods and equipment, all of which have become more sophisticated than in the early days of the barbell (DiNubile, 1991). Commensurate with this improvement in knowledge and technology are numerous, often spurious, claims by manufacturers: claims which must be evaluated critically. Fortunately, researchers too have become more interested in resistance training, which in the past was all too often founded on opinion and myth, rather than scientifically-based knowledge. In studying strength, pure research using animal models is difficult, and human studies are not without their design challenges owing to the inherent natural variability between one individual, or group, and another (DiNubile, 1991).

### **Resistance Training Modes**

A variety of available methods and equipment for improving muscular strength and endurance exist. Training systems can

usually be classified as isometric, isotonic or isokinetic. In all cases the ultimate goal is to improve physical function through the development of increased muscular strength, endurance, and power (Kisner and Colby, 1990).

Briefly: in isometric or static contractions, the muscle maintains a constant length as resistance is applied. There is essentially no change in joint position (DiNubile, 1991). "Isotonic" motion is classically defined as "constant tension" (Fleck and Schutt, 1985), although what is constant is the external load, not the tension required to overcome it, which changes with the changing effort-arm (leverage) of the muscles concerned. In the sense in which it is traditionally used then, the term 'isotonic' is a misnomer: the term 'isoinertial' is more appropriate. In so-called 'isotonic' motion the speed of contraction is not fixed (DiNubile, 1991). Isokinetic motion is contraction at a constant speed with an accommodating resistance. Speed of movement is controlled and resistance is proportional to the force exerted at each point through the full range of motion. The theoretical advantage of this mode of training is maximal muscle tension through the full range of motion (DiNubile, 1991). Since the present research is concerned with what has traditionally been termed "isotonic" equipment, the remaining review will concentrate on this mode of training. Since it is beyond the scope of the present study to presume to change terminology in widespread

use the term "isotonic" will be used here, although "isoinertial" would be more correct.

### **"Isotonic" Resistance Exercise**

Isotonic contractions are dynamic; they are either eccentric (lengthening) or concentric (shortening) and can also be classified on the basis of resistance encountered by the contracting muscle. Constant resistance procedures maintain the resistance at a stable level, although the muscles' force-generating capacity can vary considerably throughout the range of motion. In contrast, variable resistance procedures attempt to increase the resistance load on the muscle during the contraction (Katch and Drumm, 1986).

Each type of resistance imposes a different type of strain upon the contracting muscle (Pipes, 1977; 1978). During constant resistance exercise, the weight or resistance does not alter through the range of motion (DiNubile, 1991), while in contrast the force generation of the muscle varies considerably (Pipes, 1978). Pipes (1978) explains that muscles contract at differing percentages of the maximum through the range of motion when a constant resistance is used. The weight used is limited by the inherent weak point on the strength curve of the exercising muscle, since a muscles' force generating capacity can vary greatly at different points through its range of motion (DiNubile, 1991).

In other words, when a muscle contracts dynamically against a fixed load or resistance, the tension produced in the muscle increases or decreases as the muscle lengthens or shortens through the range of motion. Therefore, despite the constant resistance offered by the load, constant tension is not exerted on the muscle throughout the range of motion. Rather, maximal muscle tension only actually develops at one point in the range of motion (DiNubile, 1991). Fleck and Schutt (1985) agreed with DiNubile (1991) stating that the correct execution of free weight exercises, and the use of some types of resistance training machinery does not result in a constant tension of the muscle through the range of motion.

DiNubile (1991) explains that a position exists during a muscular contraction at which one is "weakest" and another at which one is "strongest". The weak position is often described by those involved in strength training as the "sticking point". This is the weak link during the range of motion and is often the limiting factor in the movement against constant resistance during isotonic exercise.

Variable resistance isotonic machines such as Nautilus, Eagle and Karian were developed in an effort to solve the "sticking point" dilemma encountered with constant resistance exercise. With variable resistance exercise, an attempt is made, through equipment design utilising cams, levers, and pulleys to vary the resistance experienced by the working muscle through its range of motion, i.e. to maintain constant

tension in the muscle, in order to mirror its associated strength curve (Pipes, 1977; Fleck and Schutt, 1985; DiNubile, 1991).

However, Harmon (1983) argued that the claim that variable resistance training modes accommodate muscular force capabilities may be unfounded. Although these machines undoubtedly provide a more compact, convenient, and safer form of external loading than do barbells and dumbbells, their existence has raised the inevitable question of whether they are superior with respect to strength development (Hay et al., 1982).

However, the point of contention should not be one of superior strength development, but one of applying maximal loads at multiple points in the range of motion, since the theory of strength development that provides the rationale for variable resistance exercise is based on the overload principle. This principle states that strength gains are achieved by taxing the muscle to its limit, or by requiring it to exert forces that exceed those it normally exerts (McArdle et al., 1991). Therefore, the strength benefit obtained by loading the muscle to its limit at all joint configurations in the exercise cycle is thought to be superior to the strength benefit obtained by a constant resistance that taxes the muscle to its limit only at the critical joint configuration (i.e. the "sticking point" of the exercise) (Kulig et al., 1984).

Despite these theoretic advantages, there is some doubt as to whether strength curves, or muscular force capabilities are truly accommodated by variable resistance machines, and recent research has failed to show significant strength gains in variable resistance over constant resistance exercise (Manning *et al.*, 1990). DiNubile (1991) argues that isotonic training is effective in developing strength and should be considered the mainstay for strengthening normal muscle as well as an integral part of most rehabilitation programmes. In order to evaluate the contention that strength curves are not truly accommodated, it is first necessary to study strength curves.

### **Human Strength Curves**

A further important concept in understanding strength involves the strength curve of a muscle. The peak force that can be generated by a muscle or muscle group varies through the range of motion, and this variation in peak force is called a strength curve (Canadian Association of Sports Sciences, 1982).

Each muscle or muscle group has its own unique strength curve.

Atha (1981) defined strength for the purposes of his review article as "the ability to develop force against an unyielding resistance in a single contraction of unrestricted duration". Kulig *et al.*, (1984) caution that although this is one of the best definitions yet offered for strength, it is a little too restrictive to be generally useful in a wide variety of present day exercise environments.

A more appropriate definition of strength might be the following. The strength of a muscle or homogeneous muscle group (i.e. a group of muscles that have neighbouring attachment sites, share a functional role, and act simultaneously) is the magnitude of the variable force that this contractile entity exerts on the skeletal system at the attachment site of interest (Kulig et al., 1984). Strength is therefore a localised scalar variable that may change with time at any particular attachment site of muscle activity (e.g. rest, isometric contraction, isokinetic concentric contraction) (Kulig et al., 1984).

### **Strength Curves**

Given a particular set of exercise conditions, the strength of a contractile entity (i.e. the maximum strength) may vary as a function of the joint angle (Kulig et al., 1984).

A plot of this function (maximum muscle force vs joint angle) may be defined as a strength curve. Kulig et al. (1984) point out that this definition is unattractive because of the obvious difficulties associated with obtaining the experimental force data needed to plot such curves. For the purposes of this study a strength curve will be regarded as any plot that describes the maximum muscular capability at a joint as a function of joint angle (Kulig et al., 1984).

According to the Canadian Association of Sports Sciences (1982), the shape of a strength curve is determined by two

primary factors: the length-tension effect, and the perpendicular distance between the line of pull of the muscle and the axis of the joint at which the muscle acts. When a muscle contracts at different lengths, there is a variation in the contraction force capabilities.

In general, the highest contraction force occurs at the longest possible muscle length, and conversely, at short muscle lengths, contraction force is lowest. Also greater torques are produced for a given muscle contraction if the perpendicular distance from the line of pull of the muscle and the joint axis increases. Thus, the strength curve is the relative interaction of these two primary factors (DiNubile, 1991).

Regardless of whether internal muscle forces or external resultant forces and torques are used as the basis for strength curves, such curves are important indicators of muscular capability, and they furnish the data needed to intelligently design variable resistance exercise machines and interpret findings. In rehabilitation, isotonic exercise can be performed against mechanical or manual resistance, depending on the needs of the patient. When an isotonic muscle contraction is resisted manually, the therapist may vary the resistance appropriately to meet the strength capabilities of the muscle throughout the range of motion (Kisner and Colby, 1990). It seems imperative, therefore, that individuals administering rehabilitation manually have an understanding of the relevant

strength curves so as to permit accommodating changes in the strength capabilities of the muscle during its range of motion, while mechanical resistance must also duplicate the relevant muscles force capabilities. These machines purportedly provide resistance to motion that varies through the exercise cycle in such a way as to precisely match the corresponding strength curve, or the muscles capability of exerting force (Kulig et al., 1984).

The preceding generalised definition of a strength curve - a plot of the muscle's maximum force capability as a function of joint angle - is somewhat simplistic according to Kulig et al. (1984), and can only be used in certain special circumstances. These authors state that this definition is meaningful and appropriate, provided the following restrictions are met:

1. Only one joint changes its configuration during the exercise. It is clear that if more than one joint changes its configuration during the exercise, a number of different muscles are acting at these joints, and each of these muscles would have its own associated strength curve. The problem would then be one of trying to decide which of these curves, at which joint, if any, is the representative strength curve for that multiple-joint exercise.
2. The muscular entity of interest crosses the joint which appears to be the dominant curve of the change in joint

configuration. This is necessary because many voluntary muscles throughout the body may be active during even a single-joint exercise, some of these acting to maintain the configurations of neighbouring joints. The forces exerted by these "stabilising" muscles may also change as the configuration of the involved joint changes, and therefore an associated strength curve could be plotted. This restriction is added to eliminate the possibility that the characteristic strength curve for a given single-joint exercise, would describe the maximum force exerted by a non-dominant or antagonistic muscular entity at the involved joint or by any muscular entity at an uninvolved joint (i.e. a joint whose configuration does not change during the exercise).

3. The point that changes its configuration has only one rotational degree of freedom. This is because of the implications that can arise when the involved joint has two or three rotational degrees of freedom and the exercise conditions do not restrict these angular variables in such a way that they are uniquely related throughout the exercise, then no unique characteristic strength curve will generally exist.

### **Measurement of Muscular Strength**

Realistic testing can serve as a motivational tool when progress is made. Therapists routinely use manual muscle

testing and other forms of testing such as tensiometer readings and torque output readings in order to obtain a baseline of muscle strength (Kisner and Colby, 1990). Strength is also of particular importance in considering Manual Materials Handling (MMH). It is therefore essential that strength testing procedures are undertaken prior to employment, ensuring matched worker strength capabilities and task demands, and ultimately attempting to reduce injury incidence (Garg and Saxena, 1980; Andersson, 1985; Ayoub and Mital, 1989).

A variety of methods are available for attempting to measure strength, including (i) tensiometry; (ii) dynamometry; (iii) one-repetition maximum (1 RM), and computer assisted output determination (McArdle et al., 1991; DiNubile, 1991). The following review will concentrate on the methods relevant to this research:

**(i) Cable Tensiometry**

This instrument measures the pulling force of a muscle during a static or isometric contraction in which there is essentially no change in the muscles external length. The tensiometer has the advantage of versatility for recording force measurements at virtually all angles in the range of motion. These tests are ideal for isolating and evaluating strength impairment in specific muscles weakened as a result of disease or injury. The muscle can be isolated at a specific joint angle, and this can be objectively reproduced on repeated measurement to determine the status of specific muscle groups

at the beginning of a therapeutic exercise programme. In addition, since more than one muscle group is usually activated in a particular movement, the tensiometer can be applied in many phases of the movement. This method may give a clearer picture of "strength" (or weakness) than do standard weight-lifting tests (McArdle et al., 1991).

**(ii) One-Repetition Maximum (1 RM)**

This is a dynamic method of measuring muscular strength and refers to the maximum amount of weight lifted once with correct form during the performance of a pre-determined weight-lifting exercise. To test 1 RM for any particular muscle group(s), a suitable starting weight is selected close to, but below, the subjects maximum lifting capacity. If one repetition is completed, weight is added to the exercise device until maximum lift capacity is achieved. The 1 RM technique is usually used with barbells and dumbbells, but can also be applied with most commercial exercise machines (McArdle et al., 1991). DiNubile (1991) cautions that although 1 RM may give accurate assessments of an individual's strength, there are much safer methods that expose the musculo-skeletal system, especially the inherent weak limbs, to less stress and give equally accurate information for the average individual. Despite the preceding capabilities to measure strength it remains a somewhat elusive property of muscle. Perhaps this is because it is determined by elements not totally housed

within the confines of the muscle such as fibre-types, cross-sectional area, and muscle capability. These elements include neural, metabolic, mechanical, and psychological factors (DiNubile, 1991).

### **Strength Testing In Manual Materials Handling**

Predictive tests for manual materials handling (MMH) activities have been considered in an effort to reduce the risk of low back injury by better matching of worker capacity with job demands (NIOSH, 1981). In identifying individual capacity for safe lifting, researchers have used models which incorporate epidemiological data, muscular strength and endurance, biomechanical load, physiological capacity or psychophysical capacity (Ayoub et al., 1980b; Kroemer, 1983; Snook, 1978).

Lifting has been described by Grandjean (1980) as being both static and dynamic. According to Kroemer (1983) and Ayoub and Mital (1989), most lifting in industry is performed dynamically, and therefore dynamic techniques, rather than static strength measurements, should be employed to determine a person's lifting capacity. Despite the importance of the effects of acceleration on load and techniques during a dynamic effort, several researchers have attempted to use isometric strength tests as predictors of lifting performance (Ekholm et al., 1982; Garg et al., 1980). However, isometric tests alone are not adequate predictors of dynamic performance, and

measures of the isometric strength of individual muscle groups are not necessarily good predictors of performance on tests employing other muscle groups (Keyserling et al., 1978; Jiang et al., 1986a).

Garg and Chaffin (1975) stated that although dynamic strength measurements have been found to correlate more strongly to lifting capacity than static strength measurements, static strength measures are still regarded as "reasonable weight lifting capacity predictors of occasional and repetitive MMH tasks" (Ayoub and Mital, 1989).

By comparison, dynamic strength measures of total body lifts have been identified more frequently in recent literature as predictive tests of performance. The reliability of the measurement of dynamic strength for determining a persons lifting capability has been confirmed by a number of researchers (Garg et al., 1980; Pytel and Kamon, 1981; Kroemer, 1983). Lifting machines have been used to measure isoinertial strength through incremental loading to maximum (Dales et al., 1986), and isokinetic strength through lifting at constant velocity (Pytel and Kamon, 1981). Pytel and Kamon (1981) studied isokinetic lifts in relation to maximal or sustained lifting performance and found no significant difference between isokinetic and isoinertial tests and improved prediction capability.

Dynamic lifting tests, whether isoinertial or isokinetic, appear to be meritorious, in that they involve a total body co-

ordinated action which appears to incorporate strategies or techniques of actual lifting tasks (Stevenson et al., 1989). However, it is obvious that in order to be valid, it is important that the testing procedure adopted is specific to the task, wherein the actual physical task requirements are determined.

## **PSYCHOPHYSICS**

### **Ratings of Perceived Exertion (RPE)**

According to Prusaczyk et al. (1992), ratings of perceived exertion (RPE) have been used increasingly for monitoring exercise intensity in clinical, rehabilitation and fitness programmes and in occupational settings because of their simplicity of use. However, one of the major continuing debates relates to the preferred method employed in obtaining psychophysical judgements (Morgan, 1981).

Subjective reactions to physical work have been found to correlate with work intensity and work performance, yet until recently they have not been seriously considered as constituting a possible basis for criteria in the assessment of human movement. The reason for this neglect of subjective reaction in favour of the more readily definable physiological indicators is that these reactions have been difficult to specify and measure (Gamberale, 1985). According to this author, some of the difficulties are probably simply due to a certain lack of familiarity with the use of psychophysical

methods on the part of the physiologists. However, most of these fundamental difficulties are connected with the nature of the measurement itself. Perceived exertion, being a privately experienced event, can only be measured indirectly through the use of self-report techniques. Thus, the individual's self-report constitutes a distal reaction, and the extent to which this distal reaction is a valid reflection of the proximal reaction, i.e. the reaction within the individual organism, relies heavily on the adequacy of the measurement procedure employed (Gamberale, 1985).

The applicability of subjective symptoms as criteria in the assessment of human movement will depend on factors affecting validity and reliability; that is, how well the reaction correlates with work intensity and work performance, and how well it correlates with physiological and neurological events (Gamberale, 1985). It has been suggested that no one single subjective reaction, measurement method, or experimental strategy is more adequate than others in every condition for all purposes (Gamberale, 1985). The arguments surrounding the choice of method in obtaining psychophysical results are complex, but it seems reasonable to propose that the scaling procedure chosen would be determined by the questions being asked (Morgan, 1981).

What techniques then are available to the researcher attempting to assess the subjective reactions to work? In the study of physical work a multiplicity of methods have been used

to measure exertion and fatigue at the perceptual level. In recent years, however, the assessment of perceived exertion has relied almost exclusively on two psychophysical measurement techniques: (i) ratio scaling, and (ii) category scaling (Gamberale, 1985). The latter technique is employed in this study.

#### **Physiological Basis For Ratings Of Perceived Exertion (RPE)**

Considerable research in the area of RPE has been directed towards the identification of the sensory cues which provide direct input into the "effort sense". Numerous physiological and neuromuscular parameters have been proposed as contributors to effort perception during exercise performed at a variety of intensities, modes, durations and environmental conditions (Carton and Rhodes, 1985). The focus of the research in this area has been on the identification of a primary cue underlying perception of effort (Mihevic, 1981). Investigators have assumed a variety of physiological parameters which constitute important perceptual cues during exercise (Mihevic, 1983) while attempting to find out how an individual perceives the exertion from the physical work being performed (Pandolf et al., 1978).

According to Carton and Rhodes (1985), the earliest investigations were primarily concerned with isolating cues which could be universally shown to dominate the cognitive evaluation of effort. Researchers have since recognised that, in view of the well-documented interrelationships among

physiological responses during exercise, and the integrated nature of perceived exertion, the search for a primary perceptual cue appears to present a rather simplistic attempt to probe the complex psychological dynamics of the exercise response (Mihevic, 1981). According to Mihevic (1981), the perceived exertion literature, *per se*, and the exercise physiology literature generally, both indicate that the perceptual responses to exercise must be evaluated in terms of various modifying variables including exercise intensity, exercise modality, steady state *vs* progressive exercise, and exercise duration.

#### **Central vs Local Factors**

Borg acknowledged that perception of effort was dependent upon input from both the muscular and circulatory system, and he proposed that for prolonged work, perceived exertion is most forcibly influenced by the adaptation of the circulatory system (Mihevic, 1981). Following the identification of the physiological cues which purportedly affect the perception of effort, numerous attempts have been made to assess the relative contribution of central *vs* local factors to RPE (Carton and Rhodes, 1985).

Ekblom and Goldbarg (1971) proposed a two-factor model, asserting that perceptions of physical exertion should be evaluated in terms of local factors involving perceptions of ventilatory and circulatory stress (Noble *et al.*, 1973a;

Pandolf, 1978; Mihevic, 1981; Pandolf, 1982). Noble et al.(1973a) agreed that perceived exertion is not always a function of metabolic equivalence alone, but also the stress placed on the local musculature during the activity. These researchers concluded that an increase in mechanical resistance, and therefore, local muscular strain, might also affect ratings of exertion.

Local factors are assumed to provide the primary sensory signals, while central factors act as an amplifier or modifier that potentiate the local signals in proportion to the aerobic metabolic demand (Robertson, 1982). Pandolf (1978) had earlier stated that the dominance of either local and/or central factors in the subjective estimation of exertion appears in part to be related to the amount of active muscle mass employed by the particular type of work. Originally, Ekblom and Goldbarg (1971) proposed that perception of effort was dominated by local factors during work involving small muscle groups, but that perceptual cues could be complimented by central inputs when large muscle groups are employed (Carton and Rhodes, 1985). However, it has been shown that the local components may still provide the most intense sensory stimulus, irrespective of the size of the muscle mass recruited (Carton and Rhodes, 1985).

Within the perceived exertion literature, the following variables have been categorised as central factors: heart rate, oxygen consumption, respiration rate, minute ventilation;

while the following variables have been assigned to the category of local factors: local muscular discomfort, blood lactate, mechanoreceptors, chemoreceptors, catecholamine excretion, proprioceptive factors, local fatigue, Golgi tendon organ activity and feelings from the working muscles and joint (Pandolf, 1982). However, in an earlier review, Pandolf (1978) cautioned that many of the hypothesised factors signalling local effort (mechanoreceptor and Golgi tendon organ activity, and sensations from muscle, skin, joints and ligaments) are nearly impossible to quantify.

### **Central Factors**

#### **(i) Heart Rate**

Much of the work supporting the importance of central systemic factors critical for perceived exertion has been directed at validating Borg's model which proposes that perceived exertion covaries directly with heart rate (Mihevic, 1981). Numerous other studies have since demonstrated the existence of a strong linear relationship between the two variables (Pandolf, 1978; Carton and Rhodes, 1985). The majority of studies which support the influence of heart rate in perception of effort have been correlational in nature (Mihevic, 1981), and consequently the relationship has not been investigated in cause and effect terms (Pandolf et al., 1972). Therefore, while heart rate and RPE may be highly correlated,

at no point has it been implied that these measures are causally related (Carton and Rhodes, 1985).

Pandolf (1978) reported several studies involving different types and intensities of work with regard to the above relationship and arrived at the following conclusions. Ratings of perceived exertion are "closely related" to heart rate responses at sub-maximal work levels, and this relationship is "fairly linear" irrespective of the kind of work. Other factors such as motivation, disease, endurance exercise, drugs, heat, and type of exercise have also been shown to affect the linearity of the relationship (Rejeski, 1981). Therefore, Carton and Rhodes (1985) concur that when exercise is performed under irregular conditions, the connection between HR and RPE can be disturbed. Pandolf et al., (1972) concluded that RPE does not seem to be a function of a single psychological parameter such as heart rate, but seems rather to involve a complex yet unresolved integration of several parameters. Noble et al., (1973a) conclude that heart rate, *per se*, is not the primary factor in rating the perception of exertion during work, and that other factors such as work-load and oxygen consumption may more accurately reflect physiological strain, and therefore perceived exertion. In addition to the metabolic factors, the amount of stress placed on the local musculature utilised in the accomplishment of the task can affect the ratings of perceived exertion (Nobel et al., 1973a).

In summary, it appears from the literature that the linear relationship of heart rate and perceived exertion is strong. However, the use of environmental and pharmacological manipulations or the independence of heart rate and perceptual responses suggests that heart rate is not a major input for perceived exertion. Remembering that the RPE scale was designed to follow the heart rate response to increasing exercise intensity, the linear relationship between the two variables is therefore virtually inherent during progressive exercise under neutral conditions (Mihevic, 1981).

#### (ii) Metabolic Demand

A number of investigators have suggested that  $VO_2$  provides central cues for exertion during dynamic exercise, and correlation coefficients for the  $VO_2$ -RPE relationship range from  $r = 0.76 - 0.97$  (Pandolf, 1978; Robertson, 1982). These correlations have been found for continuous and intermittent work, for work involving load carriage and for both arm and leg work (Pandolf, 1978). Investigators agree that although the perception of effort is related to metabolic demand there is no evidence that oxygen consumption is consciously monitored by the individual during exercise (Mihevic, 1981; Robertson, 1982; Carton and Rhodes, 1985). Robertson (1982) observed that the mechanisms that regulate the transmission and intensity of this sensory signal are not clearly understood.

Studies which have suggested that oxygen consumption may serve as a cue for perceived exertion have examined perceptual

differences in terms of absolute and relative oxygen requirements. Activity level, body composition, exercise mode, environmental conditions, and pedalling frequency on the bicycle ergometer have been the independent variables in these studies, and although differences in perceptual ratings have been noted at absolute exercise intensities, perceptual differences were frequently eliminated when relative exercise intensities (%  $\text{VO}_2$  max) were employed (Mihevic, 1981).

Pandolf *et al.*, (1972) suggest that  $\text{VO}_2$  is not a dominant factor in an individual's subjective rating of exercise stress, and they contend that local feelings of strain in the working muscles and joints can dominate the exertional perception to the extent that metabolically different levels of work are perceived to be equally stressful. Noble *et al.*, (1973a) support this conclusion stating that perceived exertion is not always a function of metabolic equivalence alone, but also of the stress placed on the local musculature due to factors such as increased mechanical resistance.

Carton and Rhodes (1985) concluded that  $\text{VO}_2$  *per se* is not consciously monitored, and it is more plausible that  $\text{VO}_2$ , like heart rate, is indirectly related to RPE, since the input of certain physiological parameters such as VE and blood lactate are linked to relative metabolic demand.

## **Local Factors**

Classification of a physiological or muscular response as a local factor important for perceived exertion is based on the mediation of feelings of strain in the exercising muscles and joints.

### **(1) Lactate Concentrations**

Using a variety of exercise modalities, intensities, environmental conditions, fitness levels, and continuous or intermittent exercise protocols, researchers have found strong correlations between RPE and blood lactate concentrations (Carton and Rhodes, 1985). Pandolf (1982) cautions against drawing conclusions implying causality between blood lactate concentrations and RPE, due to the correlational nature of many of the studies in question.

Unlike most of the parameters which have been suggested as primary cues influencing perceived exertion, blood lactate during increasing exercise exhibits a similar, positively-accelerating function to RPE when plotted against time (Mihevic, 1981; Carton and Rhodes, 1985). Below an exercise intensity of 65% of  $VO_2$  max however, lactate does not increase substantially for normal subjects. Trained individuals have an elevated anaerobic threshold, and therefore it can be postulated that lactate may influence perception of effort at high exercise intensities, while its contribution at lower intensities would be minimal (Mihevic, 1981).

Although some studies provide evidence which supports the role of lactate concentration as a potent stimulus for the perception of effort, the mechanism by which this influence might be mediated is uncertain (Mihevic, 1981). Several authors have suggested that pain and discomfort in the working muscles may be related to the stimulation of free nerve-endings, due to the metabolic acidosis which is induced by elevations in muscle lactate concentration (Pandolf, 1978; Carton and Rhodes, 1985).

It appears that the evidence implicating blood lactate as a perceptual cue is equivocal although there have been conflicting findings. It seems as though blood lactate concentrations may influence perception of exertion by means of some presently unidentified pathway, rather than a reduction in pH (Mihevic, 1981; Carton and Rhodes, 1985).

The review of studies presenting correlational evidence to support the influence of lactate concentration as a perceptual cue shows generally consistent results, indicating that the relationship of lactate concentration with perceived exertion is quite strong. Also, although the mechanism of lactate's perceptual impact is as yet unidentified, the muscular discomfort which typically accompanies lactate accumulation provides a source of sensory information which is readily available to conscious awareness (Mihevic, 1981).

## **Psychophysics in Industry (Manual Materials Handling)**

Muscular strength is often required in tasks involving manual handling of heavy materials. If an operator's strength is not sufficient to meet the demands of these tasks (either inherently or due to the limits of the work environment), then exertion-related injuries are more likely to occur. Therefore, in order to reduce the severity of any injuries it is essential to define the capacity limits of individuals and to operate within them (Nicholson and Legg, 1986).

It is believed that one way to prevent injuries resulting from manual handling of materials is to apply restrictions on how much a person should be permitted to lift. Such restrictions should be based on the knowledge of the lifting capabilities of the human body and the characteristics of the lifting tasks. From a physiological point of view, individual ability to perform a lifting task is limited by central factors associated with the pulmonary, circulatory and metabolic systems, and by local factors concerning muscular strength, and that of limb joints and the spinal column. From the psychological perspective, motivational factors play an important role in determining the individual capacity for labour (Gamberale et al., 1987).

On the basis of these considerations, many models have been developed to predict the lifting capacity of workers and to describe the stresses imposed on them by different lifting tasks (Gamberale, 1985). Numerous recommendations for

permissible loads have been proposed, based upon diverse criteria. Psychophysics is one of the criteria that has been used with increasing frequency (Snook, 1988). Essentially, the worker is given control of one of the task variables, usually the weight of the object being handled. All other variables such as frequency, size, height and distance moved, are controlled. The procedure is then to ask the individual to adjust his workload, i.e. the weight, to the maximum he can perform without straining himself or without becoming unusually tired, weakened, overheated, or out of breath. The worker monitors his own feelings of exertion or fatigue, and adjusts the weight of the object accordingly. Only the individual worker can sense the various strains associated with manual handling tasks, and only the individual worker can integrate the sensory inputs into one meaningful response (Nicholson and Legg, 1986; Snook, 1978; Snook, 1985).

With the aim of determining the load-handling capacity of industrial workers, Legg and Myles, (1981) have systematically used the psychophysical approach to collect estimates of workload during different MMH activities standardised in the laboratory. According to Snook (1978), a proper use of these estimates can reduce the occurrence of injuries more effectively than selecting the worker for the job, or training the worker to lift correctly.

At present there is no general agreement concerning the validity of these demands based on the usual 20-30 min of



testing. Thus, Mital (1983) was not able to validate the assumption that people can estimate the amount of weight they can actually lift for an  $8\text{h}\cdot\text{day}^{-1}$  based on an effort they perceive in 20-30 min of work. Mital (1983) also stated "... that the psychophysical method tends to overestimate the maximum acceptable weight of lift".

There appears to be some controversy about whether the psychophysically determined maximum acceptable weights obtained from a shorter period are significantly higher than those obtained from longer lifts. Mital (1983) reported that the weights selected by males and females after 8 hours were 65% and 84% of the weights selected after 25 minutes. Karwowski and Yates (1986) reported that the weights chosen by the subjects at 30 min did not differ significantly from the 4 hour values at 1, 3 and 6 lifts.min<sup>-1</sup>. However, Fernandez et al. (1991) reported that the weights selected after 8 hours were 88% (2 lifts.min<sup>-1</sup>) and 84% (8 lifts.min<sup>-1</sup>) of those estimated for a 25 min period.

Garg and Saxena (1980) found that for a 1 hour lifting task, ratings of perceived exertion for the whole body ranged from 8-18 for 3 lifts.min<sup>-1</sup> in the sagittal plane and for the floor to 0.81 m height, i.e. some subjects selected a weight which was between "very, very light" and "very light" and the upper weight between "very hard" and "very, very hard". These authors concluded that this shows that the use of psychophysical methodology on an individual basis is highly

questionable. Nicholson and Legg (1986) obtained mean RPE values of 10.7 for 27.5 min of lifting, and 11.5 at 57.5 min during a one-hour work period. Asfour et al. (1991) found that mean overall body RPE values for prolonged arm lifting ranged from 12.7 to 15.4 at 5 kg for 4-10 lifts.min<sup>-1</sup>, and 16-17.4 at 20 kg for 4-10 lifts.min<sup>-1</sup>.

#### **ENERGY EXPENDITURE AND RESISTANCE TRAINING**

Resistance training exercises are increasingly employed in training programmes of both competitive and recreational athletes. It would be advantageous for individuals to be able to calculate with some certainty the number of kilocalories consumed in a resistance or weight training work-out, since correct caloric balance is important if the individual is to maintain optimum body weight and performance (Kalb and Hunter, 1991). With a clear understanding of energy transfer, and the effects of specific training on the systems of energy delivery and utilisation, it should be possible to construct a sound training programme to achieve optimal performance (McArdle et al., 1991).

Endurance exercise has received substantial scrutiny owing largely to its relative ease of investigation and purported health benefits (Holloszy, 1983; Seals and Hagberg, 1984). Resistive type training, in contrast, has garnered much less attention, reflecting in part technical difficulties with quantifying its energy output/input and potential health risks

(MacDougall et al., 1985). A large portion of the power output spectrum of humans, therefore, has not been extensively studied, providing great opportunity for those interested in the bioenergetics of strenuous activity (Dudley, 1988).

The major objective of training is to cause biological adaptation in order to improve performance in a specific task or activity. This requires adherence to carefully planned and executed activities. Clearly, an efficient training programme is one that allocates a proportionate commitment to training the specific energy systems involved in the activity. Consequently attention is focused on such variables as frequency and length of work-outs, type of training, speed, intensity (load), duration, and repetitions of the activities; and appropriate competition (McArdle et al., 1991). A large array of different resistance training programmes exist providing a large variety of "recipes" with regard to the differing quantities of ingredients, namely load, repetitions, speed, rest, etc. Consequently large amounts of inconsistencies exist.

### **Metabolic Stress of Resistance Training**

Although various strength training modalities are effective in enhancing a muscle's force-generating capacity, these modalities provide only minimal stimulus to improve aerobic capacity and reduce body fat (Hickson et al., 1980). Undoubtedly, the stress on specific muscles is considerable in

strength training. Given the brief activation period and the relatively small muscle mass used, however, the cardiovascular and aerobic metabolic demands are small compared to those of vigorous walking or running, swimming and cycling, or any other activity utilising large muscles (McArdle *et al.*, 1991).

### **Circuit Weight Training**

Coaches, athletes and sports scientists have long subscribed to the opinion that resistance training is an anaerobic activity which will, under certain conditions, improve muscular conditioning, but will not, under those same conditions, appreciably affect cardiovascular efficiency (Peterson, 1976). However, by modifying the approach to strength training, it is possible to increase the caloric cost of exercise and bring about improvements in more than one aspect of general conditioning (Wilmore *et al.*, 1978). The approach, termed circuit weight training (CWT), de-emphasises the heavy local muscle overload of strength training to provide for a more general conditioning to improve body composition, muscle strength and endurance, and some cardiovascular fitness (Katch *et al.*, 1985; Marcinink *et al.*, 1985).

Although it is accepted that CWT programmes are effective for developing and maintaining muscular strength (Wilmore *et al.*, 1978; Gettman *et al.*, 1978; 1980), it is less clear that these programmes are aerobic (as advertised) and will develop and maintain cardio-respiratory "fitness" (Wilmore *et al.*,

1978; Gettman and Pollock, 1981). These advertisements claim that maximum cardio-respiratory or aerobic power can be achieved using particular types of strength development, but these claims, according to Gettman and Pollock (1981), have no research base.

A major goal of individuals using a circuit programme is to improve cardio-vascular conditioning, however, circuit programmes of short-term training (8-20 weeks) increase maximal oxygen consumption approximately 4% and 8% in men and women respectively (Gettman and Pollock, 1981). Fleck and Kraemer (1987) report that this increase is, however, substantially less than the 15%-20% increase in maximal oxygen consumption due to running programmes over the same period. Gettman and Pollock (1981) observed that energy cost studies indicate that heart rate (HR) and oxygen consumption ( $\text{VO}_2$ ) intensities during CWT are at minimum threshold levels for improving cardio-respiratory power. These researchers suggest that if one goal is to increase cardio-vascular endurance, CWT is the programme of choice.

Gettman (1978) studied the energy cost of CWT involving slow-speed ( $60^\circ.\text{s}^{-1}$ ) and fast-speed ( $120^\circ.\text{s}^{-1}$ ) isokinetic exercise training. 5 men completed 3 circuits of isokinetic exercises with 12 reps per exercise and 30s rest between sets. The average energy expenditures were  $9.6 \text{ kcal.min}^{-1}$  and  $9.9 \text{ kcal.min}^{-1}$  for slow- and fast-speed circuits respectively.

Hurley *et al.* (1984) found that after 16 week of a variable resistance (Nautilus) training programme,  $VO_2$  max did not change, regardless of the way it was expressed. These results, along with finding of no changes in the hemodynamic response to sub-maximal exercise after training, suggested that this form of training fails to produce adaptations in cardio-vascular function. The researcher's data on the responses to a single training session and data from previous studies (Wilmore *et al.*, 1978) indicates that one stimulus for producing cardio-vascular adaptations is lacking; i.e. the relative oxygen consumption (%  $VO_2$  max) is not sufficiently high (only 45%  $VO_2$  max) to produce increases in cardio-vascular function. Hurley *et al.* (1984) based their conclusions on previous studies which have shown that no increase in  $VO_2$  max occurs when the intensity of training is 50%  $VO_2$  max (Davies *et al.*, 1974). Ratings of perceived exertion during the Nautilus work-out demonstrated that exercising at the same  $VO_2$  as required during walking at 4 mph (45%  $VO_2$  max), produces extremely high levels of discomfort, suggesting that  $VO_2$  values were at the upper limit which could be attained during Nautilus exercise.

A more recent study (Katch *et al.*, 1985) evaluated cardio-respiratory parameters for shoulder, chest and leg exercise performed maximally on a single unit, 3-station hydraulic resistance exercise machine. 20 college men completed three 20s bouts of shoulder, chest and leg exercise with a 20s rest

between bouts and 5 min rest between exercise modes. The peak  $\text{VO}_2$  measured during the 3 hydraulic exercises was 2.1, 1.87 and 1.78  $\ell \cdot \text{min}^{-1}$  for leg, chest and shoulder exercise respectively.

In terms of energy cost, the peak metabolic intensity was approximately 6  $\text{kcal} \cdot \text{min}^{-1}$ .

Heart rate is often used to prescribe the intensity of exercise training based on a relatively strong linear relationship between the percentage of task-specific peak or maximum oxygen uptake (%  $\text{VO}_2$  max) and percent of task-specific peak or maximal heart rate (% HR max) reported for treadmill exercise and for cycling with the arms and legs (Collins et al., 1991). However, these researchers found that this relationship is not the same in all modes of low-resistance dynamic exercise, particularly if the HR/ $\text{VO}_2$  relationship on the treadmill is used as the reference.

It has been consistently reported that the HR of a given  $\text{VO}_2$  is higher during resistance weight-training than for dynamic low-resistance exercise such as treadmill running or leg cycling (Gettman and Pollock, 1981; Hempell and Wells, 1985; Hurley et al., 1984). Collins et al. (1991) found that over a range of 40%-70% of 1 RM, this type of observation is noted if  $\text{VO}_2$  and HR are expressed as a percentage of treadmill determined max values. The mechanism underlying the HR during resistance weight-training compared with dynamic low-resistance exercise at the same  $\text{VO}_2$  is as yet unknown (Collins et al., 1991). The above review indicates a large variety of testing and training

protocols on a wide range of possible equipment and machinery, yielding differing and sometimes conflicting results upon which comparisons are made and conclusions drawn. Hempell and Wells (1985) point out that one factor leading to the inconsistent findings regarding cardio-respiratory benefits of CWT is the lack of standardisation in design. CWT programmes differ in the number of repetitions performed, the number of exercises, the number of sets, the amount of resistance used, and the work-to-rest ratios. Peterson (1976) states that obviously the consequences of a resistance weight-training programme are dependent upon the method and equipment used in the programme.

It is evident that in order to make meaningful comparisons between weight training and its physiological and caloric effects on different types of equipment modalities, research methodologies need to become more rigorous and standardised in their approach, especially since different types of training yield different types of adaptation.

### **Traditional Resistance Training**

Performance of resistive-type exercise (RTE) (i.e. Olympic power weight lifting and body-building) presents power output substantially greater (10-15 fold) than that evident with endurance type exercise. Accordingly RTE relies heavily on the anaerobic enzyme machinery of skeletal muscle for energy supply, with alterations in the rate of aerobic metabolism being modest.

In studies conducted by Hickson (1980) and Hickson *et al.* (1980), in which more conventional training was performed, 3-5 sets (3 min rest between) of high resistance (80-90 % 1-RM), low repetitions (5 per set) show that resistive training for at least 10 weeks induces no increase in maximal aerobic power. These authors caution that it should be appreciated, however, that this type of training does not decrease this variable.

Keul *et al.* (1978) concluded that the energy requirements during a resistive exercise session designed to simulate competition are met exclusively through hydrolysis of high energy phosphates in skeletal muscle. This session included performing bench press, dead lift and squat in a pyramid fashion (repetitions of 10, 5,3,2,1 and 1 per set of each) with mutual loads (50, 90 and 60 kg respectively) increasing 8, 10 and 10 kg respectively and with rest between sets (2 min) and exercises ( 5 min).

A training session typically performed by body-builders to induce hypertrophy of the thigh (5 sets each of front and back squats, and leg press and extensions, with the load for each designed to induce failure in 6-12 repetitions and with an average exercise to rest value per set of 30:60s) presented marked elevations of plasma lactate (peak value of about 13.3 millimoles - 16.49 millimoles per litre) (Tesch *et al.*, 1986). A study on Nautilus equipment by Hurley *et al.* (1984) also showed copious accumulations of lactate in blood (16-17 millimoles per litre).

Taken together, these results indicate that the measure of alterations of blood variables during resistive exercise depends on the intensity (load), exercise time and exercise rest value of a given session. The amount of rest provided between sets and exercises dictates the amount of stress placed on the lactic and energy source. When rest periods are less than 1 min long, plasma lactic acid concentrations are extremely high (Noble *et al.*, 1984). This is also true, however, in CWT where relatively light loads of 40-60% of 1 RM are used (Gettman and Pollock, 1981). The relative contributions of the different enzyme systems of energy supply to the energy demands of resistive exercise have not yet been established (Dudley, 1988).

Dudley's (1988) review showed that a tremendous effort had been put forth to develop an understanding of the meaning of alterations of blood lactate during endurance exercise. Developing an understanding of changes of blood lactate consequent to resistive exercise may create much less controversy and have important practical implications. Subsequent increases in blood lactate are evident during and immediately after resistive exercise, suggesting that glycolysis makes a significant energy contribution to the effort (Hurley *et al.*, 1984; Tesch, 1987). Dudley (1988) cautioned that the relationship, if evident, however, between rate of energy supply and changes in this blood metabolite during resistive exercise has not been established.

Tesch (1987) found that the decline of the high energy phosphate and glycogen contents and the accumulations of glycogenetic/glycolytic intermediates including lactate indicate substantial activation of anaerobic energy machinery, which is reasonable considering the severity of the contraction efforts.

#### **Energy Expenditure in Industry : Manual Materials Handling (MMH)**

Various approaches have been utilised by researchers to determine MMH capacity, one of which is the physiological method which is concerned with the physiological stress on the body. Traditionally, the physiological approach has been used to assess the severity of high frequency MMH jobs since endurance has long been thought of as the limiting factor for human performance in the design of these tasks (Asfour, et al., 1991).

The maximum daily energy expenditure that a "fit" man can be expected to maintain on an habitual basis (no deleterious effects) is said to be around 4000 kcal (Edholm, 1967). Allowing for basal metabolism during the hours of sleep and energy consumed during domestic activities (2000-2300 kcal) this works out at a maximal acceptable energy expenditure, averaged over of the working day at 4.5-5 kcal.min<sup>-1</sup>; equivalent to about one-third of the maximum aerobic power of an average man (Pheasant, 1991).

Untrained individuals can sustain a level of energy expenditure equivalent to 33-50% of maximal aerobic power without lactic acid accumulation leading to fatigue. Astrand (1967) found that, left to their own devices, building workers pace themselves at about 40% of maximal aerobic power. Studies of American industrial workers have found somewhat lower figures (NIOSH, 1981). It has therefore been proposed that: "the average energy expenditure for continuous work (e.g. 8-h working day) should not exceed 33% of the workers maximum aerobic power" (NIOSH, 1981). For a "standard reference man" this works out at 5 kcal.min<sup>-1</sup>, a figure which has been widely quoted in the ergonomic literature (Murrell, 1969; Grandjean, 1988). Pheasant (1991) however, notes that insomuch as this figure is based upon the capacity of an "average" man, it will be beyond the capacity of 50% of the male population.

A number of studies have been carried out in an attempt to determine the physiological demands to prolonged (day-long) work. Asfour *et al.* (1991) examined the effects of prolonged arm lifting on endurance time and physiological responses. The upper limit of endurance time was set at 8h. These researchers found that oxygen consumption and heart rate values depended on endurance time. These values decreased with an increase in endurance time. Table I summarises the results obtained in this study.

**TABLE I:** Summary of results of endurance time and physiological responses to prolonged arm lifting (Asfour et al., 1991)

Load	Frequency (lifts.min <sup>-1</sup> )	Mean Endurance Time (min)	Mean VO <sub>2</sub> (l min <sup>-1</sup> )	Energy Expenditure (k cal.min <sup>-1</sup> )
5	4	471	0.54	2.7
5	6	426	0.56	2.8
5	8	309	0.62	3.1
5	10	237	0.64	3.2
10	4	424	0.60	3.0
10	6	362	0.68	3.4
10	8	251	0.70	3.5
10	10	191	0.91	4.55
15	4	319	0.69	3.45
15	6	258	0.77	3.85
15	18	160	0.94	4.7
15	10	110	0.95	4.75
20	4	114	0.74	3.7
20	6	90	1.03	5.15
20	8	77	1.05	5.25
20	10	49	1.16	5.8

In an earlier study, Legg and Pateman (1984) attempted to determine the relationship between lifting rate and time to exhaustion using 3 standard loads. Oxygen consumption results showed that as power output increased with increasing lifting rate for each load, VO<sub>2</sub> was observed to rise systematically. Table II summarises the findings of this study.

In 1984 Mital reported comprehensive maximum acceptable weight of load for male and female workers for 8h shifts, and compared it to data collected for 12h work shifts. Since significantly less weight (22% and 12% for males and females respectively) was accepted for 12h shifts compared to 8h shifts, corresponding heart rates and metabolic energy expenditure rates were also lower. The metabolic energy expenditure rate decreased by  $0.60 \text{ kcal}\cdot\text{min}^{-1}$  for males and  $0.3 \text{ kcal}\cdot\text{min}^{-1}$  for females when the shift duration increased from 8-12 hours. The frequency effects for 8h and 12h durations, for males and females, were very similar. In general, as the frequency of lift increased, the weight lifted decreased. The oxygen uptake of males and females nearly doubled when the lifting frequency increased from one lift. $\text{min}^{-1}$  to 12 lifts. $\text{min}^{-1}$  ( $0.42 \text{ l}\cdot\text{min}^{-1}$  ( $2.1 \text{ kcal}\cdot\text{min}^{-1}$ ) to  $0.91 \text{ l}\cdot\text{min}^{-1}$  ( $4.55 \text{ kcal}\cdot\text{min}^{-1}$ ) for males and  $0.29 \text{ l}\cdot\text{min}^{-1}$  ( $1.45 \text{ kcal}\cdot\text{min}^{-1}$ ) to  $0.57 \text{ l}\cdot\text{min}^{-1}$  ( $2.85 \text{ kcal}\cdot\text{min}^{-1}$ ) for females.

Fernandez *et al.* (1991) determined psychophysical lifting capacity over an extended period. 12 male subjects estimated their lifting capacity in a 25 min period, and then attempted to lift this weight for an 8h period under varying conditions. All 12 subjects lasted the 8h at 2 lifts. $\text{min}^{-1}$  but at a frequency of 8 lifts. $\text{min}^{-1}$  only 3 subjects completed the 8h lifting task. In the 8h period, oxygen consumption was  $0.65 \text{ l}\cdot\text{min}^{-1}$  ( $3.25 \text{ kcal}\cdot\text{min}^{-1}$ ) at 2 lifts. $\text{min}^{-1}$  and  $1.105 \text{ l}\cdot\text{min}^{-1}$  ( $5.53 \text{ kcal}\cdot\text{min}^{-1}$ ) at 8 lifts. $\text{min}^{-1}$ .

TABLE II: Summary of Results obtained by Legg and Pateman (1984)

Load	25% MLC (22.4kg)			50% MLC (44.8kg)			75% MLC (67.2kg)		
	8	10	12	4	6	8	2	3	4
Rate (lifts.min <sup>-1</sup> )	8	10	12	4	6	8	2	3	4
VO <sub>2</sub> (l.min <sup>-1</sup> )	1.55	1.79	1.86	1.41	2.79	1.98	1.17	1.52	1.9
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )	20.5	23.9	25.0	18.6	23.7	27.1	15.3	20.0	25
kcal.min <sup>-1</sup>	7.75	8.95	9.3	7.05	8.95	9.9	5.85	7.6	9.6
RPE	11.6	15.1	16.7	14.5	16.0	18.4	14.9	16.8	18

In many real working tasks, periods of intense physical activity alternate with rest periods of lighter work. In general, this is likely to maximise the total quantity of physical work the individual is able to perform during the working day - compared, for example, with working at a steady, but lower level (Astrand, 1960). In such cases, work should be designed so that the overall energy expenditure - averaged over the working time - and taking into account both work and rest - remains within acceptable limits (Pheasant, 1991).

## CHAPTER THREE

### METHODOLOGY

#### INSTRUMENTATION

##### Isometric Maxima

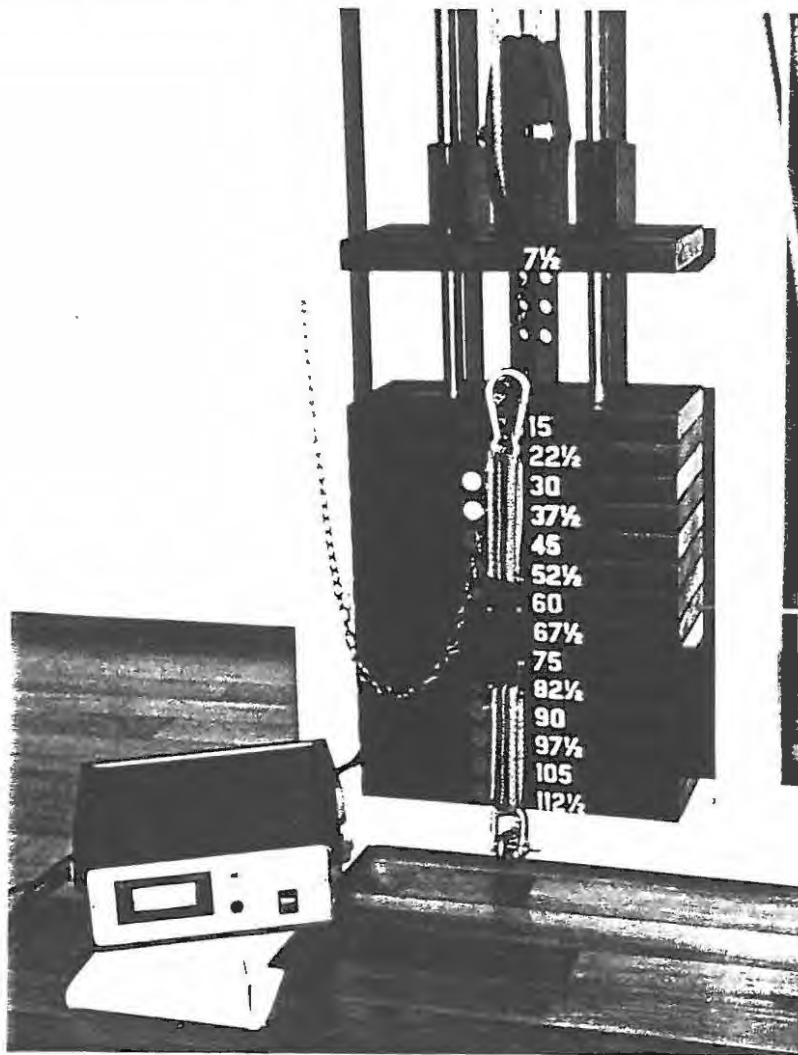
Strength of the musculo-skeletal system was assessed using a Digital Myometer (MIE System). This system involves a Strain-gauge tensiometer and a digital display unit. The tensiometer measures the tension generated by a muscle group in newtons, at the point of attachment of the machine to the musculo-skeletal system.

The tensiometer was the central bit in a fixed strap (unstretchable by the range of forces encountered). At the base of each piece of machinery was an anchor-pin to which one end of the strap was attached. The free end of the strap was attached to a movable pin, which was inserted into the centre shaft of the weight stack (see Figure 1). The movable pin was inserted into the appropriate hole of the centre shaft to achieve the desired angle at which the maximal isometric effort was to be performed. Therefore, for each angle of isometric contraction, the pin was removed, adjusted accordingly, and re-positioned.

##### Metabolic Analysis

Metabolic analysis of fixed-rate isoinertial work was

conducted with the use of a Morgan Oxylog, which is a portable oxygen analyzer useful for assessing the energy expenditure of movement *in situ*. However, unlike traditional methods of gas analysis, the Oxylog only analyses the oxygen content of expired air. In addition, it is capable of determining the volume of air which is moved per minute ( $V_a$ ), and the total amount of air moved over a given period of time. Similarly, this analyzer measures the total amount of oxygen



**FIGURE 1:** Connection of the MIE System to the weight stack prior to isometric testing.

consumed over a period of time, and the minute  $VO_2$ . The Oxylog does not have the capability of analyzing the  $CO_2$  content of the expired air, and thus is limited in its application to activities which rely predominantly on the aerobic metabolic pathways for energy production. Therefore, without this facility ( $CO_2$  analysis), it is impossible to make any statements about the extent to which an activity is reliant upon anaerobic metabolic pathways. If it is utilised for analyzing the energy expenditure of high intensity, short duration activities, the data will not be truly representative of the energy required for the specific task being performed. This technology-inherent limitation forced assessment only of very light (50% max) energy cost levels. Figure 2 shows the Morgan Oxylog connected to a subject before testing.



**FIGURE 2:** Attachment and positioning of the oxylog on a subject prior to testing.

## PROCEDURES

### Isometric Maxima

The range of motion of each unit of exercise equipment was determined by placing a Leighton Flexometer on the lever-arm and getting large and small subjects to move the lever-arm through the full range of motion.

Once the total movement angle of each piece of equipment had been determined, the four points in the range of motion at which the isometric testing was to be conducted, had to be calculated. The first point was always at or near the beginning of the range. This initial testing angle was limited by the position of the first hole in the centre shaft of the weight stack. Therefore the initial testing position was not at the absolute beginning of the movement. The fourth and final testing position was at the outer limit of the range of motion as determined by the subjects. The remaining two angles were taken as equidistant angles through the range of motion. Thus, for a range of motion of  $90^\circ$ , the initial testing angle would be at or near  $0^\circ$ , the final testing angle at  $90^\circ$ , and the intervening angle would be at or near  $30^\circ$  and  $60^\circ$ .

To secure the system a movable pin was placed in the appropriate hole of the centre shaft associated with the angle at which isometric testing was to take place. Subjects were required to move the lever-arm until it could no longer be moved, due to the strap of the myometer system, and at this point to make a maximal isometric contraction. Three maximal

contractions at each point in the range were required. The highest force generated was recorded as the maximal isometric contraction.

In order to assess the overall musculo-skeletal function required in a particular movement, the reading which appeared on the digital display unit in force units (newtons) was converted to torque units of newton metres (Nm). This calculation of the movement or torque produced by the musculo-skeletal lever system requires that the applied force must be multiplied by the perpendicular distance from its line of action to the axis of rotation, i.e. "the extrinsic lever-arm". However, due to the use of cams on the machinery involved in this study, the radius of the cam at each point of isometric testing had to be incorporated into the calculation. More detailed derivations of the equations used to determine the muscular torque on each piece of machinery is given in each of the analyses in Chapter Four.

#### **Cam Radius Measurement**

At each of the four pre-determined points during the movement angle at which isometric testing was to be conducted, the radius of the eccentric cam had to be determined. This radius was attained by measuring the distance from the centre of the pivot arm to the rim of the cam at right angles to the line of the pull of the cable (Figure 3).

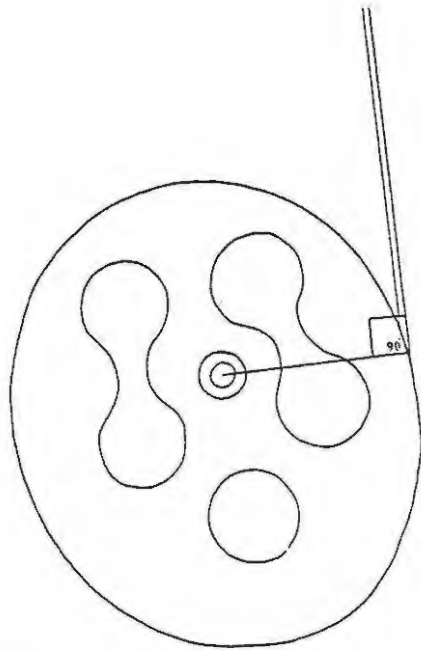


FIGURE 3: Measurement of cam radius on isoinertial machinery

**One-Repetition Maximum (1 RM).**

This refers to the maximum amount of weight lifted once, with correct form, during the performance of a pre-determined weight lifting exercise. A suitable weight is selected close to, but below, the subject's maximum lifting capacity. If one-repetition is completed at that weight, weight is added to the exercise device until maximum lift capacity is achieved. It must be noted, however, that on certain machines, some individuals were able to lift more than the mass comprising the entire weight stack.

**Preferred Rate.**

Readings are updated on the Morgan Oxylog at a rate of

once per minute. Therefore subjects were required to perform the exercise for a minimum of one minute. Consequently, in order to standardise the work rate, a preferred rate for one minute had to be determined.

After having determined their 1 RM's, subjects were required to work for one minute at the designated submaximal stress level under analysis, i.e. 10% max or 30% max. During this time the number of repetitions completed was recorded.

The mean number of repetitions per minute at each of the two submaximal stress levels under analysis were calculated and statistically analyzed using a related T-test to determine if there was any significant difference between the two stress levels on each piece of machinery. No significant difference was noted so, the same rate of motion (reps.min<sup>-1</sup>) was used for both effort levels on each piece of equipment.

#### **Metabolic Analysis.**

Analysis of the energetics of fixed-rate work on the 'pec-fly' and knee extension units involved a sex-based assessment in which subjects were required to perform submaximal efforts at steady state at 30% and 50% of each individual's 1-RM for one minute, at a rate of 27 reps.min<sup>-1</sup>. Data were collected at the end of one minute. For analyses on the 'pullover' and 'abdominal' units, subjects were required to perform continuously at 10% and 30% max for 10 minutes at a preferred rate of 25 reps.min<sup>-1</sup>. The rate was set by metronome.

Metabolic data were collected every minute during the 10 minute exercise period.

Metabolic data collected included total  $O_2$  consumption ( $l.min^{-1}$ ), MET equivalents and energy expenditure ( $k.cal.min^{-1}$ ) were derived from the raw data. Energy expenditure ( $k.cal.min^{-1}$ ) in this study is determined on the basis of 5 kcal per litre of oxygen as a means of converting oxygen consumed ( $l.min^{-1}$ ) to  $kcal.min^{-1}$ .

Throughout the metabolic analysis subjects were required to ventilate in accordance with standard practice at the pre-set rate of movement: expiration before, or during, concentric work and inspiration during eccentric work.

### **Psychophysical Analysis**

This analysis was conducted with the use of the Borg Scale to determine ratings of perceived exertion. For the 'pec-fly' and knee extension analyses subjects gave ratings of exertion for central (cardio-vascular) and local (muscular) responses immediately after the completion of the exercise bout. In the analyses of the 'pullover' and 'abdominal' pieces of machinery, subjects supplied the same feelings of exertion (central and local) every 2 minutes during the 10-minute exercise bout.

CHAPTER FOUR  
RESULTS AND DISCUSSION  
ANALYSIS ONE : 'PEC-FLY' UNIT

**INTRODUCTION**

The 'pec-fly' machine is designed to provide a position-controlled medium for exerting muscular tension against resistance during isoinertial vertical lifts of adjustable mass units. The design is such that pulleys change the direction of force-application to provide a uniplanar horizontal flexion and extension of the shoulder joint (elbows flexed 90° throughout) through a range of about 130° (See Figure 4).

The design aims to standardise operator position comfortably and safely so that only the motion of horizontal flexion-extension through the prescribed range is possible, and to do this in a manner in which load-increments can easily be re-set commensurate with increases in strength over a period of training. The range and step-increments of weights, and the adjustable seat-height both indicate a design intended to accommodate users of diverse levels of strength and body-size.

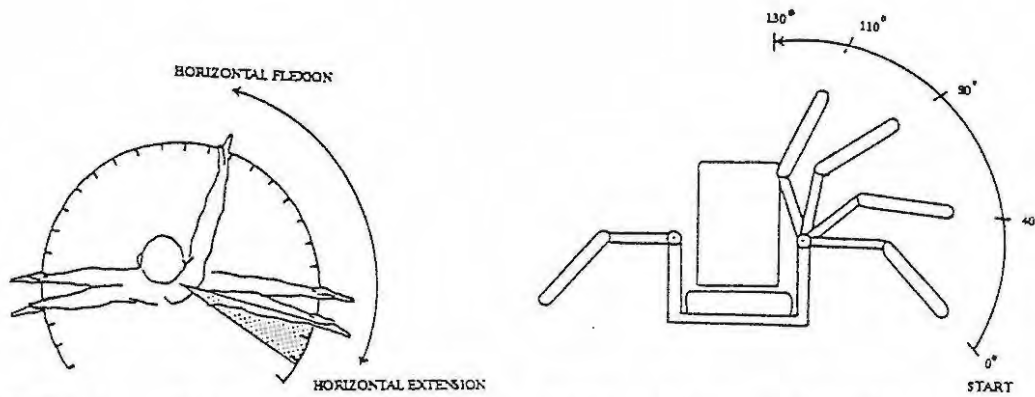
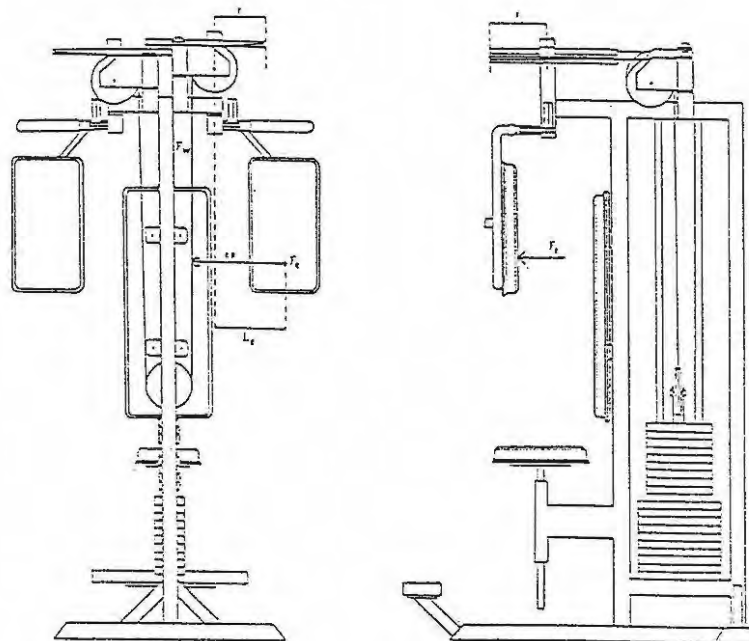


FIGURE 4: Plan view giving some idea of the amount of horizontal extension required at the start of the motion. (Shaded zone is the limit of normal extension allowing for inter-individual variation).



- Where:
- $ea$  is the effort arm from the centre of the shoulder joint to the centre of the forearm pad in metres
  - :  $L_e$  is the lever arm from the centre of the cam to the centre of the forearm pad in metres
  - :  $F_e$  is the force exerted against the machine in newtons
  - :  $F_w$  is the myometer reading in newtons.

FIGURE 5: Derivation of the equations used to calculate musculo-skeletal torque on the 'pec-fly' machine.

## SECTION 1 : ENGINEERING ANALYSIS

Musculo-skeletal leverage through a normal range of motion is such that muscle force available for movement varies depending upon lever configuration, muscle length, perception of stress and other factors. In attempting to determine the muscular torque on the 'pec-fly' unit certain equations had to be derived. Gowitzke and Milner (1988) state that the moment of force,  $M$ , combined with a force such as  $E$  (effort) or  $R$  (resistance) acting on a lever is defined as the product of the force and the perpendicular distance to its line of action from the axis. Clearly the resistive moments must be exactly counterbalanced by the effort moments to achieve equilibrium. Thus, for the 'pec-fly' (Figure 5):

$$F_w \cdot r = F_e \cdot L_e \dots\dots\dots \text{So: } F_w = F_e \cdot \frac{r}{L_e} \quad (1)$$

Since the perpendicular distance from a line of force to an axis through the fulcrum is the moment arm, then  $MA_e \cdot E = MA_r \cdot R$  (where  $MA_e$  is the moment arm of the effort and  $MA_r$  is the effort arm of the resistance). The equation for torque ( $T$ ) or moment of force:  $T = f \cdot d$  (in which  $f$  is the effort or resistance force and  $d$  is the moment arm or perpendicular distance from the line of force to the axis), provides the equation of moment equilibrium for muscle torque on the 'pec-fly' unit:

$$T_m = F_e \cdot ea \quad (2).$$

However, (1) and (2) have different fulcra of balance.

Therefore by simple substitution: From (1):  $F_a = F_w \cdot \frac{r}{L_a}$

Therefore:  $T_m = F_w \cdot \frac{r}{L_a} \cdot ea$

$$: T_m = F_w \cdot r \cdot \frac{ea}{L_a}$$

i.e. Muscle torque = Myometer force . cam radius .  $\frac{\text{skeletal lever}}{\text{machine lever}}$

The object of ergonomic re-design is to match the mechanical requirements of the machine with the biomechanical characteristics of the human musculo-skeletal system; in other words, to ensure that the torque required by the machine changes at the same rate and in the same direction (increase or decrease) as the torque exerted by the user through the range of motion, i.e.  $F_w \cdot r = F_a \cdot L_a$ .

A different weight-load can be chosen for each trial, but the weight  $F_w$  is fixed (isoinertial) within a given trial. The changing pattern of the force applied on the forearm pad is determined by the user (i.e. is based on individual capacity limits). Thus the only parameters which can be adjusted by the designer are the cam radius ( $r$ ) and the machines' lever ( $L_a$ ). Designing an eccentric cam with changing radii is easier and more economical than designing an adjustable lever. Consequently this lever-arm length is accepted as fixed.

The cam radius must increase or decrease in tandem with increases or decreases of force exerted by the user ( $F_a$ ), in this

way ensuring that the torque required by the machine increases or decreases at the same rate of increase or decrease as the torque exerted by the user through the range of motion (See Figure 6).

Figure 7 depicts the cam radii required to ensure that maximal muscle force is exerted throughout the range of motion, and the cam radii presently installed in the unit under analysis; radii which fail to achieve that purpose (Figure 8 shows the shape of the redesigned cams based on the radii given in Table III and Figure 7).

A design weakness in many commercially available 'pec-fly' machines exists in the non-adjustability of the starting position, which consequently unsafely stretches the muscles of the anterior chest wall in many users.

The length to which a muscle is stretched before contracting has considerable effect upon the subsequent force of contraction, such that maximum force is achieved when this stretch is 20-30% above the muscles' normal resting length (Klausen, 1988). Further increases (or decreases) in pre-contraction length result in sub-optimal force outputs. On the 'pec-fly' machine analyzed the angle between forearm rest and back support is fixed at 45°, which means that larger users must horizontally abduct their arms through correspondingly increased angles to assume the starting position.

**TABLE III:** Mean isometric horizontal shoulder flexion force, derived torque and associated positional and machine specification factors, for a combined-sex group of active young adults.

PARAMETER	DATA				DERIVATION
	0 START	40	80	110 FINISH	
Degrees of Flexion					(measured)
Cam radius (m)	0.200	0.213	0.225	0.252	(measured)
Myometer ( $F_w$ ) (N)	613	663	714	614	(recorded)
Torque ( $T_w$ ) (Nm)	127.7	146.6	166.6	159.4	( $F_w \cdot r_{ea}/LE$ )
Force exerted against machine ( $F_s$ ) (N)	471.5	543.2	617.9	595.1	( $F_w \cdot r/LE$ )
Adjusted Cam radius (m)	0.202	0.232	0.263	0.252	(based on 0.252 set at 110°)
Adjusted $F_w$ (N)	632.2	631.9	633.5	632.5	( $T_w \div \text{adj cam}$ )

The present design accommodates arm-access by only the smaller user and even then the access is awkward. Users expressed inconvenience, if not discomfort, in having to get one arm in place and then the other: the manoeuvre was found to be awkward as it placed the leading shoulder under excessive passive horizontal extension while access was

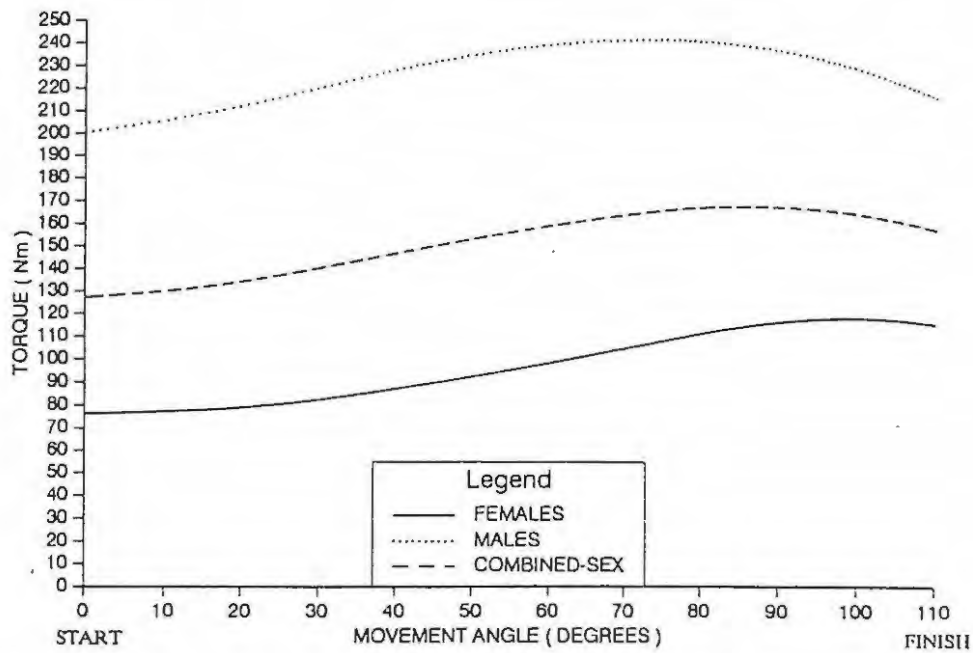


FIGURE 6: Sex-based and combined-sex differences in isometric torque produced at four test points through the range of motion on the 'pec-fly' machine.

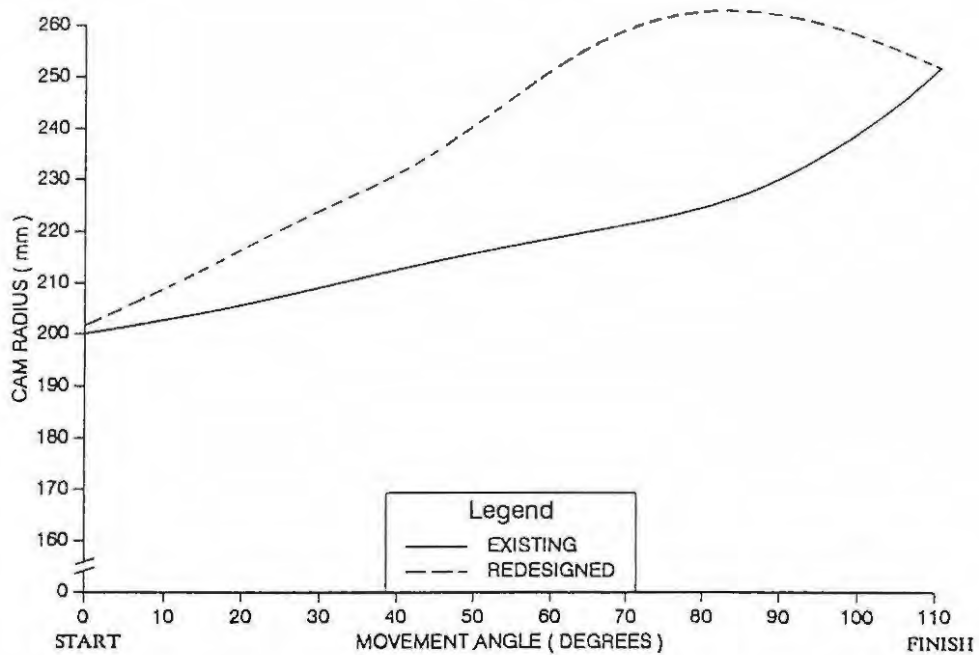


FIGURE 7: Existing and redesigned eccentric cam radii to show the need for improvement.

gained by the second shoulder. Arm-access should be based on an above-average sized male using a bilateral horizontal extension in which the arms go no more than 15° behind the plane of the backrest. Under these conditions all smaller users will need to horizontally extend the arms somewhat less than 15° behind the frontal plane in order to assume a starting position (Figure 4). This would ensure a pre-stretch of the exercising muscles which is closer to the physiological optimum. The simplest practical solution would be to have an adjustable wedge which permitted the existing range of motion for suitable cases, but normally provided a slightly reduced range of motion, with less potential for overstress at the horizontal extension limit (See Figure 9).

A further design fault noted was that once users had placed their forearms against the pad, excessive wrist flexion was required in order to grasp the hand grip in its designed position which was anterior to the forearm pad. However, due to the length-tension relationship, as the extent of wrist flexion increases clenching the fists becomes increasingly difficult. Also the antagonistic wrist extensors become disproportionately lengthened. In extreme wrist flexion, making a fist is unnatural and palmar flexors are weak. Correction of this fault could be cost effectively implemented by moving the hand grip flush with the forearm pad, the users forearm and wrist in a straight line. This correction is shown in Figure 9.

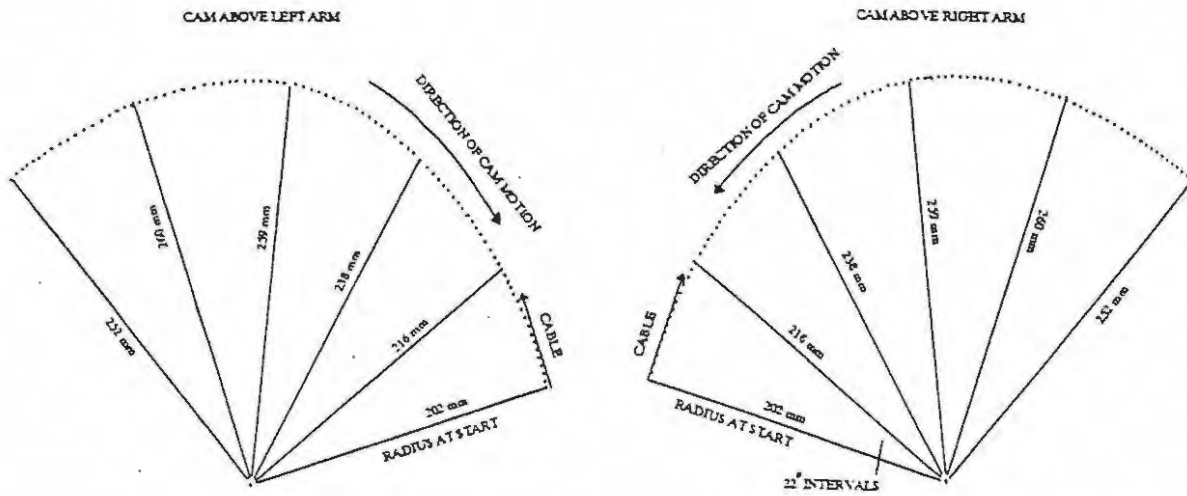


FIGURE 8: Redesigned 'pec-fly' cam shapes based on radii given in Table III and Figure 7.

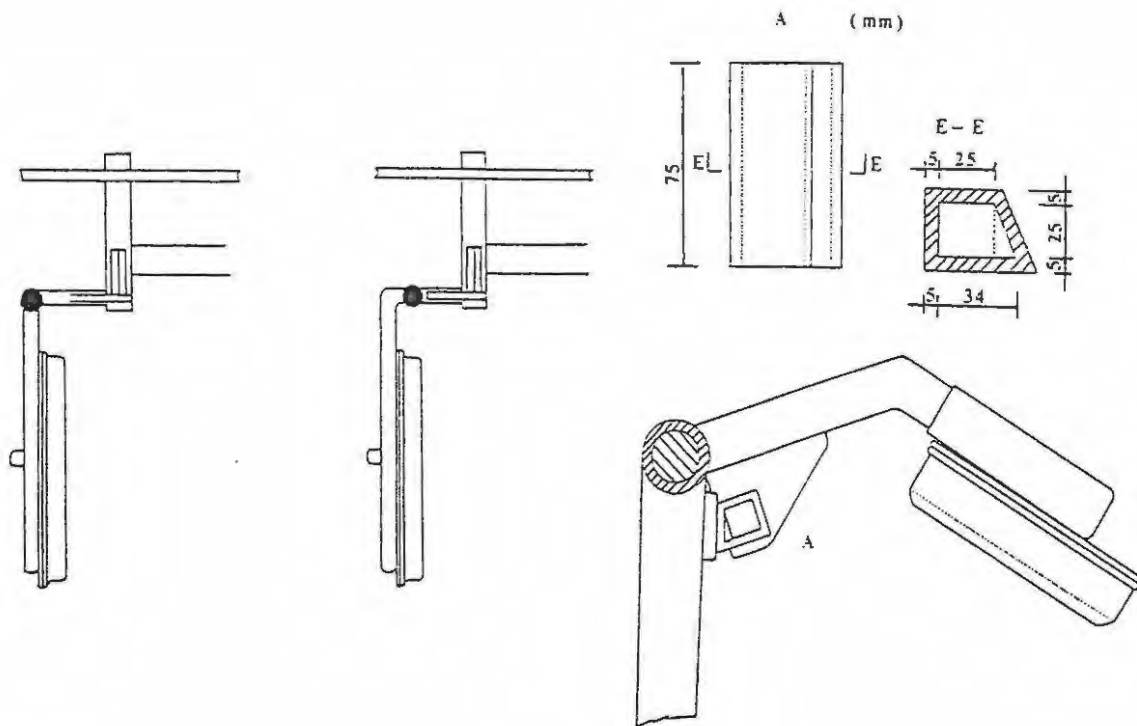


FIGURE 9: Repositioning of hand-grip (shown in cross-section as black circle) to reduce wrist flexion (left), and adjustable wedge permitting varying starting positions (right).

## SECTION 2: MUSCULO-SKELETAL ANALYSIS

### 2.1 Isometric Torque Maxima

A group of healthy, active young adults of both sexes participated in this study. TABLE III summarises the combined-sex maximal isometric force and torque data of the group at FOUR selected positions through the range of motion. Figure 10 shows the pattern of isometric maxima generated by a mixed-sex group of active young adults without upper-extremity clinical histories. Males and females responded similarly, their isometric maxima varying in parallel through the range of motion, although the males were consistently significantly stronger. The pattern similarity between the sexes confirmed that no substantive sex-related design modifications were needed, and that any adjustable features on the machine would be justified on the basis of body-size, not sex per se.

### 2.2. Relevant Muscles of the Shoulder Joint and Shoulder Girdle

Figure 11 shows the relevant musculature utilised in horizontal flexion and extension with the elbows flexed at 90°. Detailed explanations of the origins, insertions and innervations of these muscles can be found in Appendix I. Figure 11 shows the origin, course and insertion of the primary muscles utilised in horizontal flexion and extension.

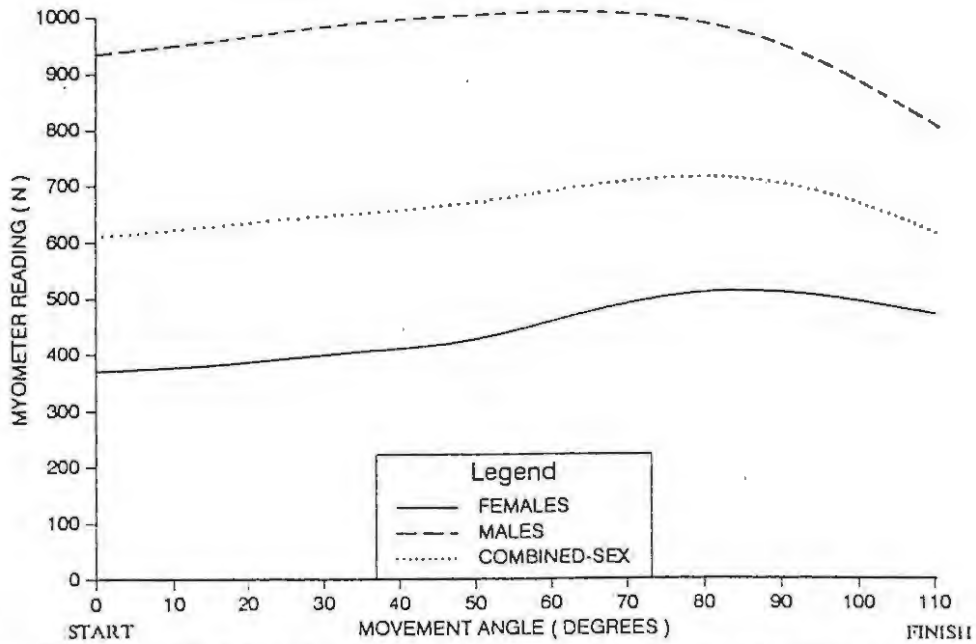
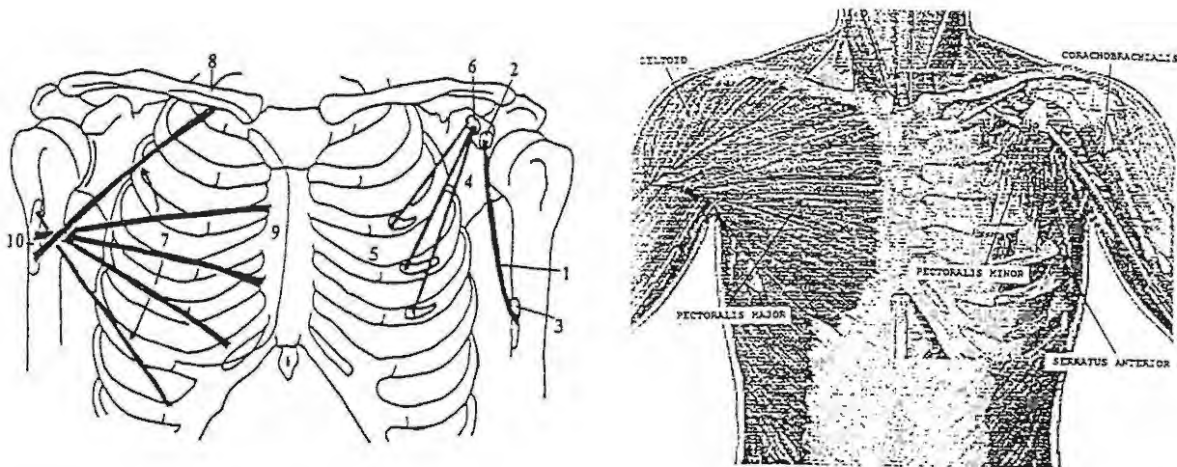


FIGURE 10: Combined-sex and sex-based differences in maximal isometric force through the range of motion for the 'pec-fly' machine.



WHERE: (1) Coracobrachialis; (2) Coracoid process; (3) Crest of lesser tubercle on humerus; (4) Pectoralis minor; (5) 3rd-5th ribs; (6) Pectoralis minor insertion on coracoid process; (7) Pectoralis major; (8) Anterior surface of the clavicle; (9) 2nd-6th ribs; (10) Pectoralis major insertion on crest of greater tubercle.

FIGURE 11: Anatomical site (right), and origin course and insertion of musculature used in the 'pec-fly' movement.

### SECTION 3 : METABOLIC ANALYSIS

This analysis consisted of a determination of the metabolic cost of performing at selected submaximal isoinertial levels and rates. The metabolic analysis involved a sex-based energy-cost assessment in which subjects were required to perform fixed-rate submaximal efforts at steady-state. Two effort-levels were imposed: 30% and 50% of each individuals 1-repetition maximum (1 RM).

A user-analysis revealed an overall preferred rate of movement on the 'pec-fly' unit. This rate of movement (27 reps.min<sup>-1</sup>) was subsequently set by metronome, and the subjects analyzed were constrained to exercise continuously at this rate for one-minute at each of 30% 1 RM and 50% 1 RM while ventilating through a portable oxygen meter (See Chapter 3).

Table IV summarises the metabolic findings. After calculating the 30% and 50% relative loads it was noted that these loads did not always correspond to a load on the weight stack. Therefore it was necessary to use a load on the weight stack which was nearest the relative load calculated from the 1 RM. Thus the relative loads moved during the metabolic analysis given in Table III are the mean values of the actual loads moved and are not true 30% and 50% values. As expected the metabolic cost of work on this unit was modest (See Figure 12). This is typical of activities in which muscular strength

rather than aerobic power predominates. Although there was some contribution to the total energy demand from aerobic sources, most of the energy was produced anaerobically, which tends to be the norm in strength training. This could have been due to the duration of the activity, which was only (60s), and was the case even at low loads of 30% 1 RM for, males and females. It is difficult to express, in quantifiable terms, the actual energy expenditure associated with the anaerobic component of the total energy expenditure. It may well be that psychophysical data provide a better indication of the extent of the total amount of "work" done than measured aerobic indicators of energy expenditure under these conditions. Ratings of perceived exertion recorded at 30% and 50% 1 RM in this evaluation are far higher than expected if only the aerobic energy expenditure is considered (See Section 4).

In practical terms, the 'pec-fly' unit allows one to develop muscular strength and/or muscular endurance. Both are predominantly anaerobic activities and therefore in terms of a training response, only the anaerobic metabolic pathways would be stressed significantly. If aerobic conditioning was the goal of a training programme, the subject would benefit substantially more by using a cycle ergometer or similar apparatus rather than the 'pec-fly' unit. Obviously, the 'pec-fly' unit does not lend itself to purposes for which it was never intended: it is a muscle building, not a weight-

losing device.

The mix of exercise intensities and durations reasonably possible on this unit stimulates carbohydrate utilization predominantly, a condition not optimally beneficial for weight-loss.

TABLE IV: Mean metabolic response to work on the 'pec-fly' machine at 30% and 50% max. (Standard deviations in brackets).

	30% max		50% max	
	MALE	FEMALE	MALE	FEMALE
Relative Load (kg)	17.22 (4.75)	5.71 (1.22)	30.28 (8.88)	8.57 1.34
O <sub>2</sub> (ℓ)	0.38 (0.16)	0.23 (0.08)	0.93 (0.18)	0.45 (0.14)
Ve (ℓ.min <sup>-1</sup> )	15.00 (6.04)	11.00 (4.89)	36.71 (2.93)	18.00 (5.44)
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )%	4.83 (1.90)	4.29 (1.38)	10.24 (1.77)	7.74 (1.96)
METS	1.38 (0.54)	1.23 (0.39)	2.93 (0.50)	2.21 (0.56)
k cal.min <sup>-1</sup>	1.95 (0.78)	1.27 (0.38)	4.16 (0.64)	2.32 (0.59)

NOTE: Mean Male Max (1 RM) was 56.7 kg f(SD 16.4)  
Mean Female Max (1 RM) was 17.5 kg f(SD 3.5)

**TABLE V:** Female data, in percentage of male data (100.F/M) on the 'pec-fly' unit.

	30% max	50% max
O <sub>2</sub> (ℓ)(%)	60.5	48.4
Ve (ℓ)(%)	73.3	49.03
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )(%)	88.8	75.6
METS(%)	89.1	75.4
k cal.min <sup>-1</sup> (%)	65.5	55.8

NOTE:  
 Female 1RM = 30.9%  
 Female 0.3 RM = 33.2%  
 Female 0.5 RM = 31.0%

Table V summarises the relative performances of the females in the sample. Interestingly the female loads constitute only about 31% of the male loads at 1 RM (Figure 13), this despite the fact that some males were able to lift at least the whole weight stack on the 'pec-fly' unit. The values given at 0.3 RM and 0.5 RM are based on the relative loads moved given in Table III. At equivalent relative loads, energy expenditure for females was 65.5% and 55.8% of the males at 30% and 50% 1 RM respectively. Clearly it is the absolute load and not the relative load which determines energy expenditure.

Since females are able to lift only about 30% of what males lift on the 'pec-fly' unit, energy expenditure will be lower for females. The male/female load proportions may reflect the disproportionate strength advantage in the upper extremities of males.

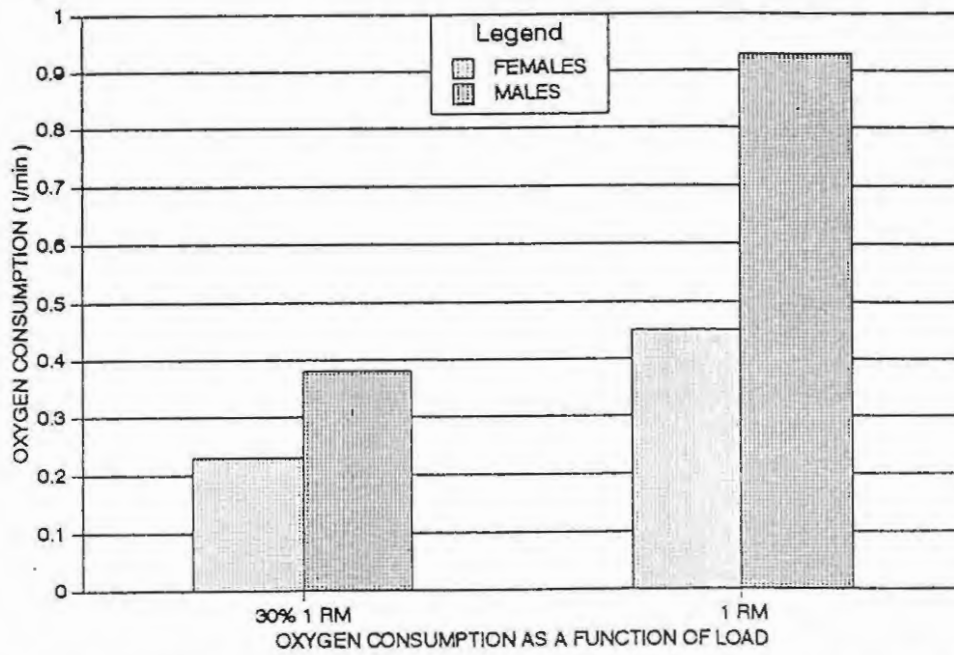


FIGURE 12: Mean oxygen consumption values at 30% and 50% 1 RM on the 'pec-fly' machine.

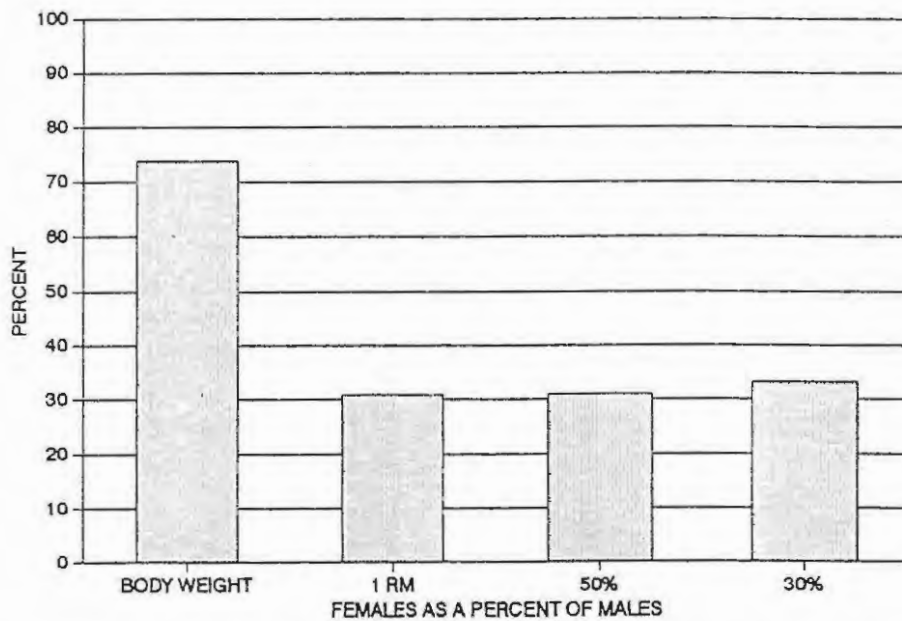


FIGURE 13: Differences based on sex: female body-weight and loads moved (as a percentage of male levels) on the 'pec-fly' unit.

#### SECTION 4 : PSYCHOPHYSICAL ANALYSIS

Determination of maximal acceptable-loads for fixed-rate, specified duration activity by psychophysical methods provides insight into goal-setting and programme-development strategies and may suggest equipment re-design. Referring to Table IV, it is clear that the absolute loads at 30% and 50% 1 RM are quite different for males and females: males always move heavier absolute loads than females at the same percentage of their max. Figure 14 shows that, in spite of the absolute load differences between sexes, the ratings of perceived exertion (RPE) are quite similar at each relative load. At 30% 1 RM males and females rated perceptions of exertion as being "fairly light" to "somewhat hard". At 50% 1 RM these ratings were between "somewhat hard" and "hard" for both sexes.

Ratings of perceived exertion appear to be related more to the relative load (30 or 50% 1 RM) than to the absolute loads (kg) at each relative load.

Furthermore, RPE values for arms ('local') do not appear to be very different from cardiovascular ('central') RPE values. This is due to the nature of the activity. Due to the relatively short duration (60s) and the small proportion of the total musculature utilized, "central" stimuli probably did not contribute much to perceptions of exertion.

The ratings of perceived exertion at both 30% and 50% 1 RM reflect a higher intensity of work than is indicated

by either measured oxygen consumption ( $\ell \cdot \text{min}^{-1}$ ) or derived energy expenditure ( $\text{kcal} \cdot \text{min}^{-1}$ ). This is probably a consequence of anaerobic stimuli producing much of the input for perceptions of exertion at both 30% and 50% 1 RM.

The awkward starting position may have been another factor which influenced ratings of perceived exertion, particularly at the higher loads (50% 1 RM).

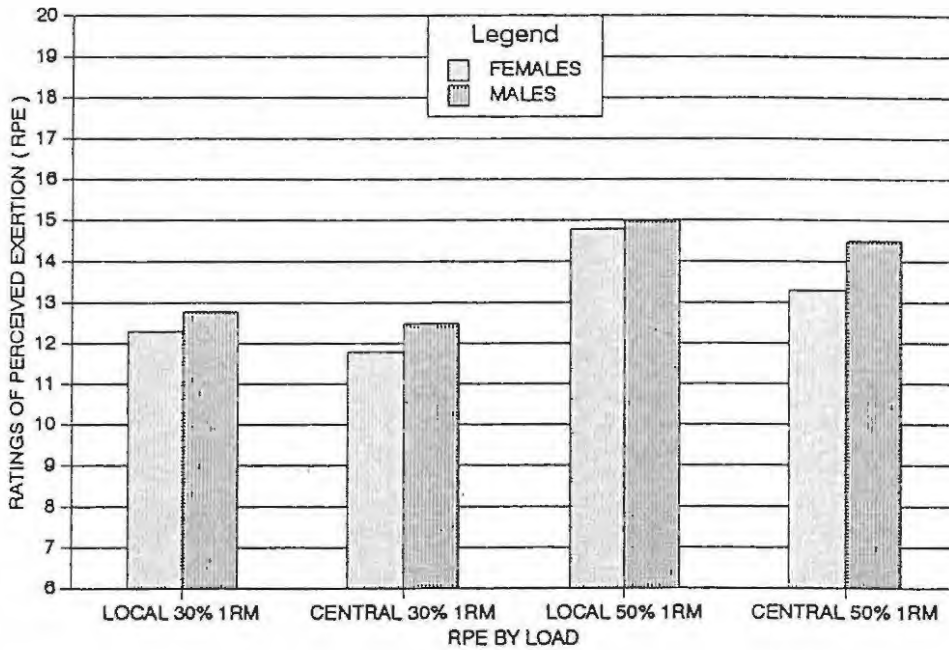


FIGURE 14: Ratings of Perceived Exertion as a function of load on the 'pec-fly' machine.

## SUMMARY

The eccentric cams on the 'pec-fly' unit were found to be the wrong shape and were redesigned according to isometric maxima. Awkward manoeuvres were required to attain the starting position prompted the installation of a wedge allowing variation in the starting position.

The musculo-skeletal analysis indicated that males were consistently stronger than females, with females moving only about 31% of male loads. Metabolic analysis showed that metabolic costs of performing at 30% and 50% 1 RM on this unit was modest. The psychophysical analysis showed that RPE at 30% and 50% 1 RM reflected a higher intensity of work than was indicated by either measured oxygen consumption or derived energy expenditure.

Based on this integrated analysis it was concluded that the anaerobic energy pathway was primarily taxed, and consequently this unit allows an individual to develop muscular strength and/or muscular endurance and not to lose weight.

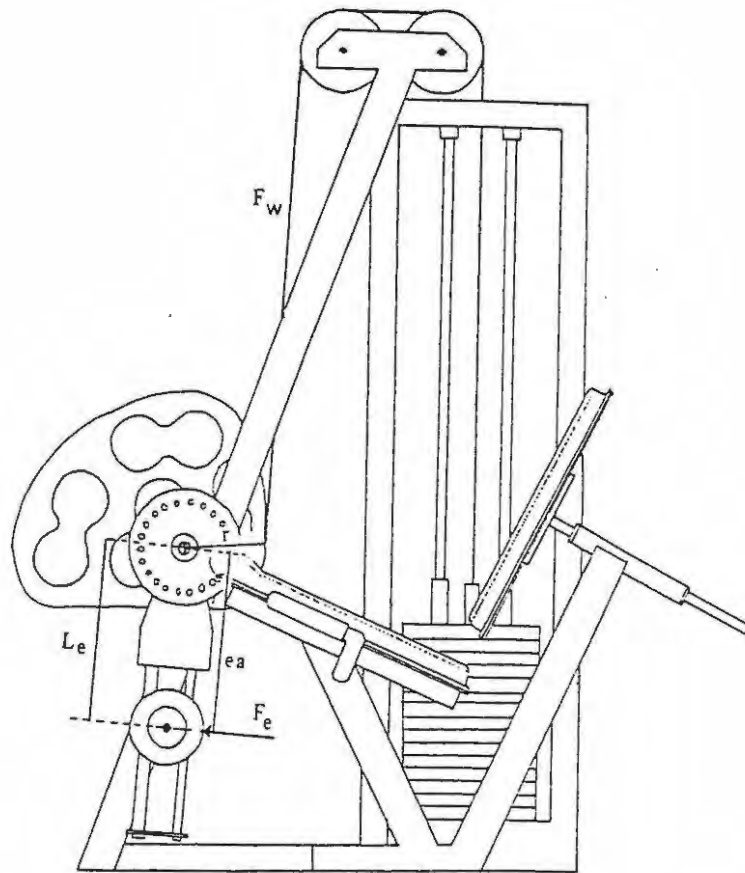
## ANALYSIS TWO : KNEE EXTENSION UNIT

### INTRODUCTION

The knee-extension unit permits seated bilateral knee extension-flexion through approximately 80% of the range of motion of the knee joint (about 110°, of an average range of 140°). The seating arrangement and position of the shin pad are such as to provide a position-controlled isoinertial vertical lift of adjustable loads, by arc-motion of the leg about a stable knee.

The clear intent of the design is to facilitate convenient load-adjustments commensurate with operator capacity, and to provide a training effect only for the quadriceps muscles (knee extensors), which work concentrically as the load is raised and again eccentrically as the load is lowered: the knee flexors are not exercised by either motion.

The range and step increments of the weights, and the adjustable back rest and leg pad indicate a design intended to accommodate users of diverse levels of strength and body size.



- NOTE :
- :  $ea$  is the effort arm from the centre of the shoulder joint to the centre of the pad.
  - :  $L_e$  is the machine lever arm from the centre of the cam to the centre of the shin-pad.
  - :  $F_e$  is the force exerted against the machine.
  - :  $F_w$  is the myometer reading in newtons.
  - :  $r$  is the cam radius from the centre of the cam to the cable.

**FIGURE 15:** Relevant levers used in the derivation of equations to calculate musculo-skeletal torque on the knee extension unit.

## SECTION 1 : ENGINEERING ANALYSIS

The presenting problem to be solved in the design of this, and all such equipment, is to devise an accommodating resistance system to adapt to changes in musculo-skeletal leverage through the normal range of motion of the joint in question. Typically the torque-development capacity of a joint is greatest at its mid-range and reduces either side of mid-range as the muscle's own lever arm distances decrease. The presence of an eccentric cam signals a design-attempt to accommodate to anatomical leverage changes at least on a "one-size-fits-all" basis.

Figure 15 depicts the levers relevant to the knee extension unit. In deriving the equations required to determine muscular torque, it was first necessary to ensure that the resistive moments were exactly counterbalanced by the effort moments in order to achieve equilibrium. Therefore for the knee extension unit:

$$F_w \cdot r = F_e \cdot L_e \dots\dots\dots \text{So: } F_e = F_w \cdot \frac{r}{L_e} \quad (1)$$

The equation of moment equilibrium for muscle torque on the knee extension unit, based on the product of the force (effort or resistance) and the moment arm at a perpendicular distance from the line of force to the axis, is:

$$T_m = F_e \cdot ea \quad (2)$$

From (1)  $F_e = F_w \cdot \frac{r}{L_e}$

$$\text{Therefore: } T_m = F_w \cdot \frac{r}{L_e} \cdot ea$$

$$: T_m = F_w \cdot r \cdot \frac{ea}{L_e}$$

However, (1) and (2) have the same centre of rotation.

$$\text{Therefore } \frac{ea}{L_e} = 1$$

$$\text{So: } T_m = F_w \cdot r$$

i.e. Muscle torque = Myometer force. cam radius.

On this unit the pattern of force as applied to the shin-pad varies with the user's own leverage. If the user altered the position of the shin pad, for reasons of perceived comfort, the factors  $ea$  (anatomically-based) and  $L_e$  (machine-based) were altered together, since  $ea/L_e = 1.00$ . The only parameter relative to these equations which was free to alter by design was that of the cam radius ( $r$ ). This factor made design modifications on this unit both feasible and simple. The re-design object, then, is to ensure that torque demands made by the unit exactly matched the rate of change in musculo-skeletal torque outputs through the user's range of motion.

A group of young adults without lower extremity clinical histories was tested at four isometric positions of knee flexion ( $108^\circ$ ;  $72^\circ$ ;  $36^\circ$  and  $0^\circ$ ). Data for both sexes were pooled since the design must cater for all users. Figure 16 shows the changing pattern of torque of males, females and combined-sex groups, which exactly as expected, peaks about mid-range of total knee excursion.

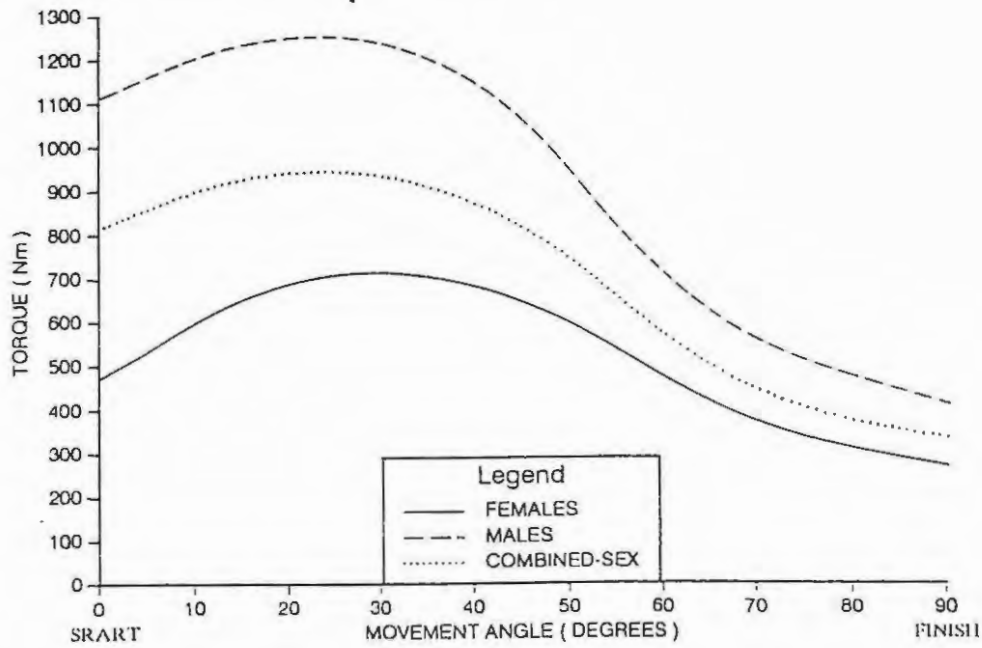


FIGURE 16: Musculo-skeletal torque as a function of four positions in the range of motion on the knee extension unit.

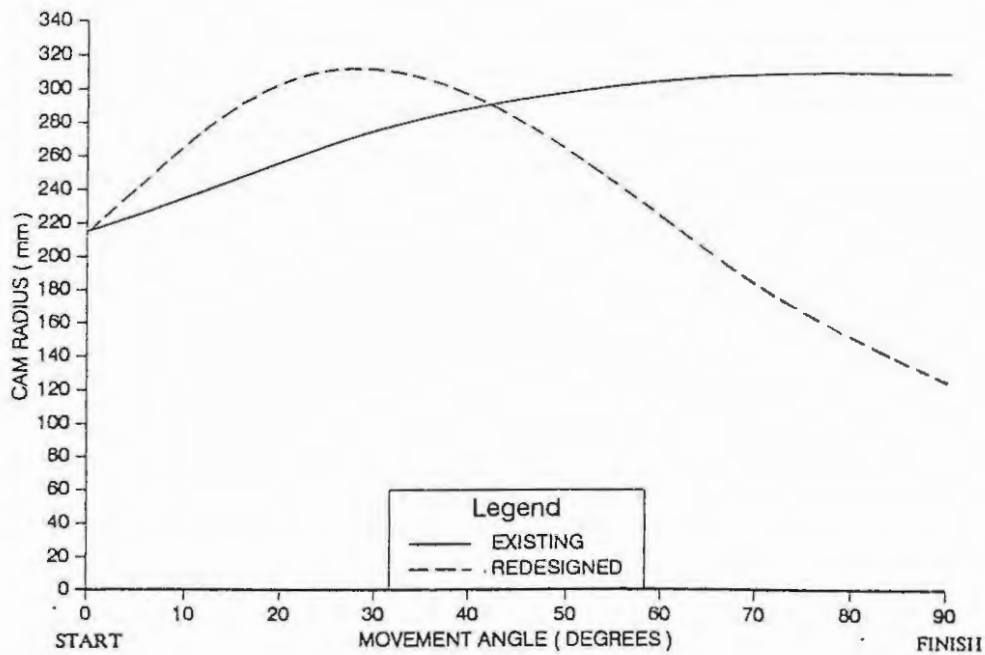


FIGURE 17: Existing and redesigned cam radii on the knee extension unit.

**TABLE VI:** Mean isometric knee extension force, derived torque and associated positional and machine specification factors, for a combined-sex group of active young adults.

Parameter	Data				Derivation
	108° Start	72°	36°	0° Finish	
Position (deg. flexion)					(measured)
Cam Radius (m)	0.215	0.275	0.305	0.31	(measured)
Myometer (Fw) (N)	814.57	932.29	580.79	333.93	(recorded)
Torque (Tm) (Nm)	175.14	255.22	180.50	103.52	Fw.r
Force Exerted against machine (Fe) (N)	175.14	255.22	180.50	103.52	Fw.r/L <sub>a</sub>
Adjusted cam radius (m)	0.215	0.313	0.222	0.127	based on 0.215 set at 120°
Adjusted Fw (N)	333.6	333.62	333.64	333.93	(Tm ÷ adj cam)

Figure 17 shows the design flaw in the present system: the existing cam radius continues to increase as the knee extends while, through the majority of the range permitted by the machine, the torque of the human user progressively

diminishes with decreasing skeletal leverage. Also depicted in Figure 19 are the dimensions the cam should have assuming existing and desirable cam radii are the same when the knee is in flexion in the starting position. The required and redesigned cam shape, based on radii from Table VI and Figure 17, is depicted in Figure 18.

In certain clinical situations individuals may only be allowed to work through the last 30° of knee extension as in the case of patellar malalignment in which *vastis medialis* must be specifically stressed (Orthopaedic advice: personal communication), while in a commercial setting individuals may wish to selectively stress the *vasti* by working through the final 30° of extension. This is usually permitted by pegging the shin-pad arm in the required numbered hole depending on the desired range of motion. On the machine analyzed, however, this totally alters the training effect on the knee and worsens the effects of the accommodating cam, since, by simply moving the shin-pad arm to the desired position (final 30° of extension), the cam is still working through the initial 30° of extension, placing an incorrect accommodating stress on the musculature. It was noted that it was possible to unpeg the shin-pad arm, hold it down vertically, and then manually move the cam. What this means is that it is possible to hold the shin-pad arm down vertically, move the cam until the cable is at the beginning of the relevant range of leg extension to be performed, and place a peg in the associated un-numbered hole, beneath the

blocking-arm, in order to limit cam movement to the required range of motion. The shin-pad arm is then moved to the beginning of the range of leg extension to be stressed. Therefore, by following the above procedure, an individual working through a limited range of leg extension could do so at the appropriate accommodating resistance on the cam. Thus, the use of the un-numbered peg-holes vastly increases the versatility of this exercise unit, a practice however, which could be dangerous in non-expert hands. The blocking bar to the right of the seat would have to be lengthened, with blocking pads placed on the top and underside of this structure.

There was a further aspect of concern in the present design of the seat. Clearly there has been an attempt to lean the subject back, which is good (a declined seat helps to 'hug' the user into the unit and it increases the knee flexion angle at the start), but this has been done by tilting the whole chair 23° while retaining a 90° seat-to-back relationship. This design takes no account of the length-tension relationship of an important knee extensor, **rectus femoris**, which is relatively 'flaccid' with the hip flexed 90°. It was noted that invariably when seated subjects were extending maximally there was a tendency to decrease the extent of thigh-on-trunk flexion in order to increase the length-tension relationship of the two-joint **rectus femoris**. In the unit under investigation subjects who were maximally stressed by the weights provided all tend to elevate their buttocks (i.e. extend at the hip).

The present seat design inhibits *rectus femoris* from contributing as it should to knee extension and therefore places a disproportionate demand on the one-joint knee extensors (*vasti*).

But the extent of knee extension is also a function of the passive tension in the bi-articular hamstrings: in the present 90° seat the last 10°-15° of knee extension is sub-optimal even without any weight offering resistance, for the simple reason that the hamstrings are too stretched by the seated position to facilitate terminal extension. Repeated testing with small and large subjects showed that the 90° seat is sub-optimal for full exploitation of the *quadriceps femoris*.

A more versatile arrangement, which can be cost-effectively constructed, would be to keep the seat where it is, but to adjust the angle of the back-rest beyond 90° as needed, so that the knee extensors become involved. Research showed that a sizeable performance increase can be expected from this.

At the same time it is useful also to be able to selectively exercise only the one-joint knee extensors and a simple and inexpensive back-rest hinge providing limited adjustments is proposed. At virtually no cost-increase this would make the unit much more versatile.

It was also noted that the angle of the inclined seat resulted in subjects having to grasp the hand-grips with the wrists in radial deviation, causing unnecessary discomfort. Consequently the angle of the hand-grips was altered to bring

the wrists into a more neutral position. Figure 21 shows the suggested design modifications of the back rest and hand-grips.

Obviously, whether intentional or not, one effect of the tilted seat is to increase the range of knee flexion at the start of the movement (i.e. to facilitate movement in the inner range of total knee extension) and this effect should not be sacrificed.

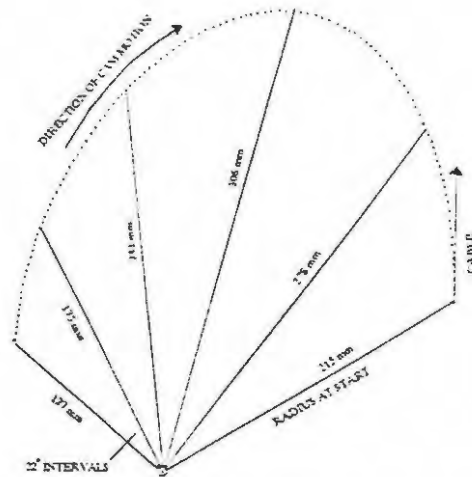


FIGURE 18: Redesigned cam shape based on radii from Figure 17 and Table VI.

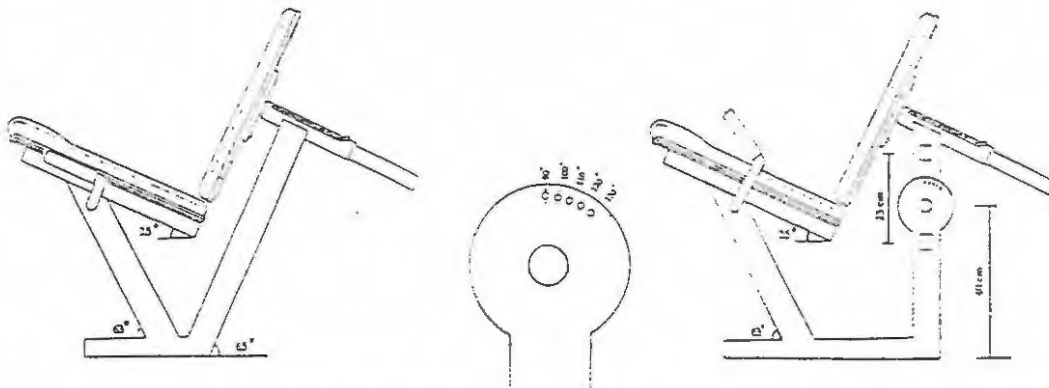


FIGURE 19: Adjustable back rest modification permitting alteration between 90° and 120° with respect to seat, and change in hand-grip angle on the knee extension unit.

## SECTION 2: MUSCULO-SKELETAL ANALYSIS

### 2.1 Isometric Torque Maxima

The mixed-sex isometric force maxima and torque data at four selected positions through the range of motion, of a group of healthy, active young adults who participated in this study, are summarised in Table VI. Figure 20 shows the isometric maxima varying in parallel through the range of motion for males and females, with females being consistently weaker than males.

No substantive sex-related design modifications were needed as a result of this pattern similarity between the sexes confirming that any adjustable modifications on the unit under investigation would be justified on the basis of body size, not sex per se.

### 2.2 Relevant Muscles of the Knee

The **quadriceps femoris** cover almost entirely the front and sides of the femur. They consist of four muscles, of which **rectus femoris**, acting on two joints, runs in a channel formed by the three single-joint muscles (the **vasti**). These three muscles arise from the shaft of the femur, which they surround, from the trochanters to the condyles; lateral to **rectus femoris** is the **vastus lateralis**, medial to it is **vastus medialis** and under it is **vastus intermedius** (See Figure 21). The proximal and distal attachments and course of the muscles utilised in knee extension are shown in Figure 21, while detailed descriptions of these muscles can be found in Appendix II.

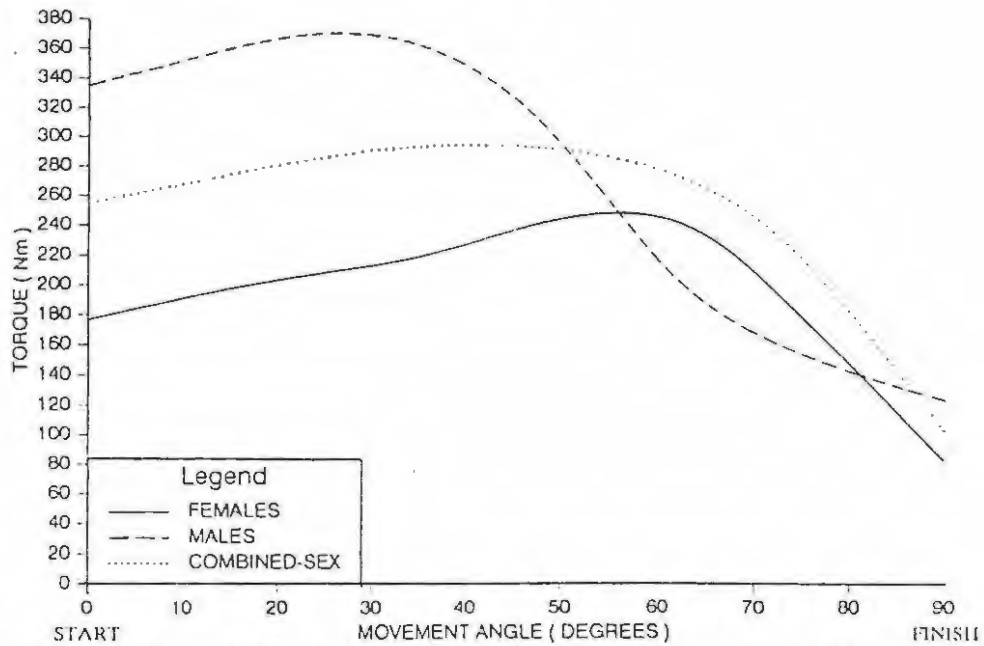
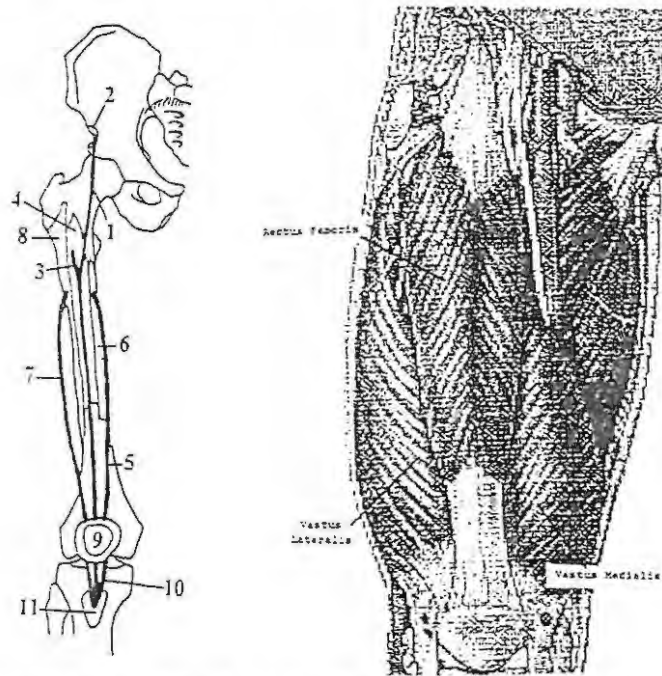


FIGURE 20: Sexed-based and combined-sex differences in isometric maxima produced at four test-points through the range on the knee extension unit.



WHERE: (1) Straight head of rectus femoris; (2) Anterior inferior iliac spine; (3) vastus intermedius; (4) Anterior and lateral surface of the femur; (5) Vastus medialis; (6) Medial lip of linea aspera; (7) Vastus lateralis; (8) Lateral surface of the greater trochanter; (9) Patella; (10) Patellar ligament; (11) Tibial tuberosity.

FIGURE 21: Origin, course, insertion (left) and anatomical sites of anterior thigh muscles.

### SECTION 3 : METABOLIC ANALYSIS

The sex-based metabolic analysis involved an energy-cost assessment in which subjects were required to perform fixed-rate submaximal isoinertial efforts. Two effort-levels were imposed; 30% and 50% of each individual's 1-repetition maximum (1 RM). Subjects analyzed were required to move continuously at a rate of 27 reps.min<sup>-1</sup>, set by metronome, for one minute at each of 30% 1 RM and 50% 1 RM while ventilating through a portable O<sub>2</sub> meter (See Chapter 3).

The metabolic findings of this analysis are summarised in Table VII and shown in Figure 22. The mean values of the relative loads given in Table VII are not the loads calculated from 30% and 50% 1 RM, but the relative loads actually moved during the metabolic analysis. The calculated 30% and 50% 1 RM loads did not always correspond to a load on the weight stack. Consequently, it was necessary to use the load on the weight stack which most closely corresponded to the calculated 30% and 50% 1 RM loads. The metabolic cost of work on this machine was moderate (Figure 22), as was expected of such activities involving muscular strength rather than aerobic power. Although there was a certain energy demand from aerobic sources, most of the energy appears to be produced anaerobically. This was primarily due to the intensity of the exercise - a combination of both the short duration (60s) and the rate (27 reps.min<sup>-1</sup>). This was the case for both males and females at 30% 1 RM and 50% 1 RM.

**TABLE VII:** Mean metabolic responses to work on the knee extension machine at 30% and 50% max (Standard deviations in brackets)

	30% max		50% max	
	MALE	FEMALE	MALE	FEMALE
Relative load (kg)	20.00 (0.00)	13.50 (4.87)	35.00 (0.00)	24.38 9.66
O <sub>2</sub> (ℓ)	0.72 (0.19)	0.40 (0.10)	0.84 (0.21)	0.53 0.05
Ve (ℓ.min <sup>-1</sup> )	25.86 (4.13)	15.60 (4.22)	36.23 (4.23)	21.03 (1.63)
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )	9.00 (0.80)	6.94 (1.54)	11.09 (0.98)	8.77 (0.83)
METS	2.57 (0.23)	1.98 (0.44)	3.17 (0.28)	2.51 (0.24)
k.cal.min <sup>-1</sup>	3.50 (0.96)	1.99 (0.44)	4.20 (1.07)	2.37 (0.64)

NOTE: Mean male max (1 RM) was 75.00 kg (SD 0.0)  
 Mean female max (1 RM) was 58.04 kg (SD 10.2)

**TABLE VIII:** Female data, in percentage of male data(100.F/M) on the knee extension unit.

	30% max	50% max
O <sub>2</sub> (ℓ)%	55.6	58.9
Ve (ℓ)%	60.3	58.0
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )%	77.0	79.1
METS%	77.0	79.2
k cal.min <sup>-1</sup> %	56.9	56.4

NOTE:  
 Female 1 RM = 64% Male  
 Female 0.3 RM = 67% Male  
 Female 0.5 RM = 69.7% Male

However, it is difficult to quantitatively distinguish the energy expenditure associated with the anaerobic component for the total energy expended during the activity.

From these results, the knee-extension unit appeared to emphasise the use of the anaerobic metabolic pathway. This reflects the machine being used to develop or enhance muscular strength and/or muscular endurance. Table VIII summarises the relative performance of the females in the sample. The female loads constituted about 64% of the male loads at 1RM (See Figure 23). Females tend to be about 70% as strong as males, with a range of 59 to 84% depending on the muscle groups tested (McArdle *et al.*, 1991). In this case, however, it must be noted that the male 1 RM was machine-limited (that is, all male subjects could lift the whole weight stack of 75 kg, which was not necessarily their 1 RM). In contrast, the female subjects all lifted their 1 RM below machine capacity. The values given at 30% and 50% 1 RM (see Table VIII) are based on the relative loads shown in Table VII.

At equivalent relevant loads, energy expenditures for females were 56.9% and 56.4% of the males at 30% 1 RM and 50% 1 RM respectively. The females in this study were able to move about 60% of the male loads on the knee-extension unit, and energy expenditures at 30% max and 50% max for the females were almost 60% of those of the males.

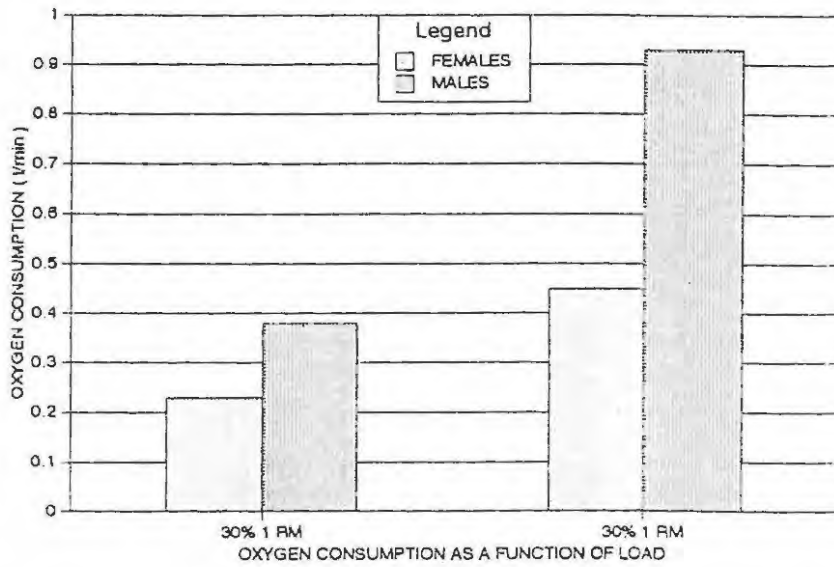


FIGURE 22: Mean oxygen consumption at 30% and 50% 1 RM for males and females on the knee extension unit.

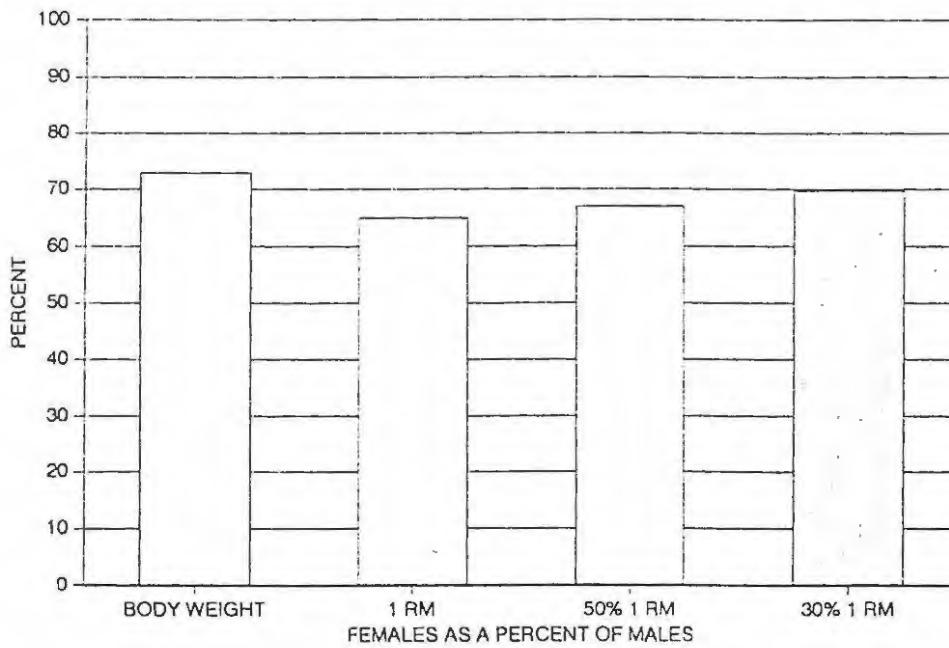


FIGURE 23: Female performance on the knee extension unit as a percentage of male performance.

#### SECTION 4 : PSYCHOPHYSICAL ANALYSIS

The absolute loads at 30% 1 RM and 50% 1 RM are quite different for males and females (Table VII) - females always moving lighter absolute loads than males at the same relative load. The ratings of perceived exertion (RPE) are quite similar at each load, despite these absolute load differences between sexes (Figure 24).

At 30% 1 RM, males rated exertion in the legs ("local" RPE) from "hard" to "very hard", and females from "somewhat hard" to "very hard", while cardiovascular ("central" RPE) ratings ranged from "somewhat hard" to "very hard" for males and "light" to "hard" for females.

At 50% max, the males perceived rating of leg exertion was "very hard", and female responses ranged from "very hard" to "very, very hard". In contrast, "central" ratings for males were from "somewhat hard" to "very hard", and for females ratings were "somewhat hard".

The high ratings of perceived exertion in the legs and the relatively low ratings from central RPE at 30% and 50% max reflect a higher intensity of work than is indicated by oxygen consumption ( $\ell \cdot \text{min}^{-1}$ ) or calculated energy expenditures ( $\text{k cal} \cdot \text{min}^{-1}$ ) at the same relative loads (Table VII). This tends to support the argument for a predominantly anaerobic pathway present in this type of activity. Consequently, it is anaerobic stimuli producing much of the input for perceptions of exertion at both 30% and 50% max.

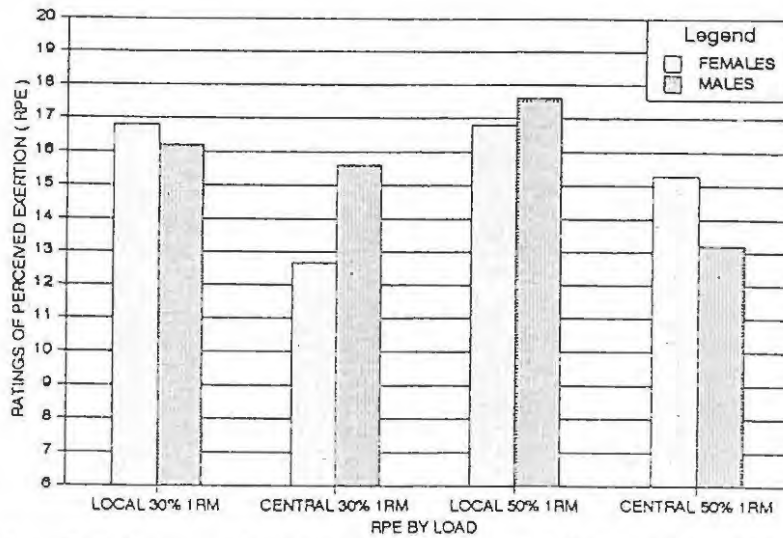


FIGURE 24: Ratings of perceived exertion and relative load on the knee extension unit.

### SUMMARY

Based on the musculo-skeletal analysis it was discovered that the knee extension unit could be made more versatile by having an adjustable back-rest, allowing an individual to relatively stress either the one-joint *vasti* or the two-joint *rectus femoris*, as desired. The existing cam shape did not accommodate to user muscle torques and was redesigned accordingly. The hand-grip angle was altered to reduce radial abduction.

Measured metabolic cost on this unit was modest. The RPE in the legs were high, while central ratings of perceived exertion were relatively low, reflecting a higher intensity of work than indicated by either energy expenditure or oxygen consumption. Based on this interdisciplinary analysis, it was concluded that the knee extension unit emphasises anaerobic metabolic pathways at the two stress levels analyzed, indicating that the machine be used to develop or enhance muscular strength and/or endurance.

## **ANALYSIS THREE : SHOULDER PULLOVER UNIT**

### **INTRODUCTION**

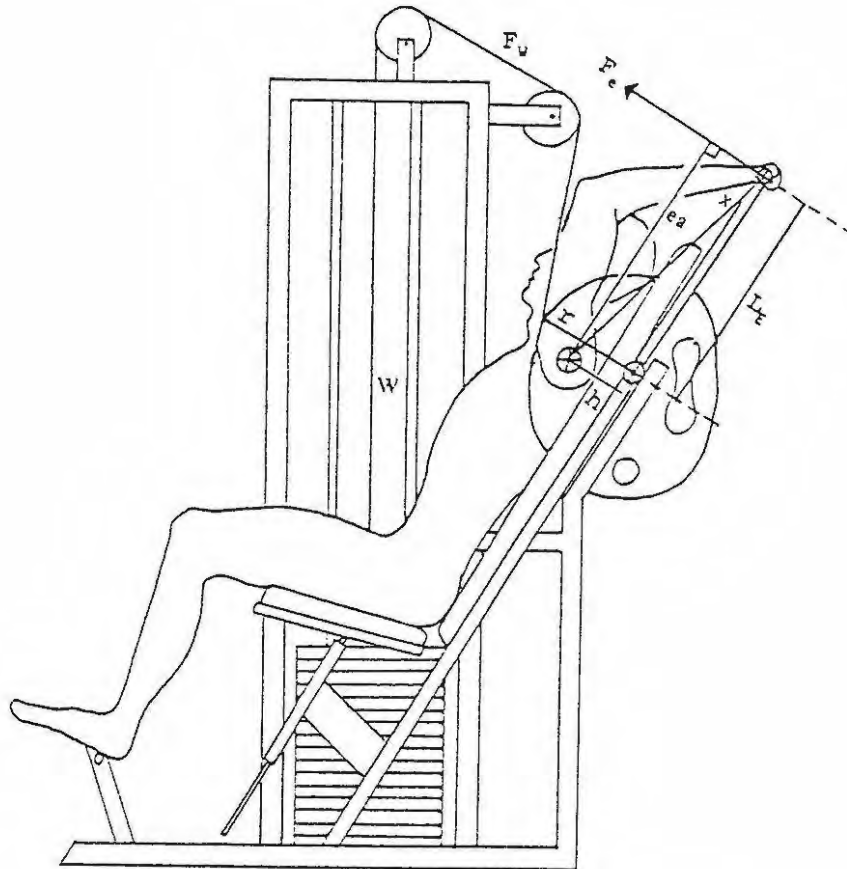
This machine is designed to provide a seating arrangement that allows a position controlled isoinertial vertical lift of adjustable loads during bilateral vertical flexion and extension of the shoulder joint through a range of approximately 140°.

The design is such as to standardise operator position comfortably and safely so that load adjustments commensurate with operator capacity can easily be reset, while providing a training effect for the muscles of the upper back, chest and shoulders.

The range and step-increments of the weights, and the adjustable seat-height indicate a design intended to accommodate users of diverse levels of strength and body size.

### **SECTION 1 : ENGINEERING ANALYSIS**

When a muscle contracts dynamically against isoinertial resistance, the tension produced in the muscle increases or decreases as the muscle lengthens or shortens through the range. At certain parts in the range, the muscle-bone lever works more favourably than at others, so that the constant load in isoinertial situations exerts a variable stress on the muscle(s) moving that load. Therefore, despite the constant load, "isotonic" effort is limited by its inability to impose maximal tension and work demands at all points on a muscle



- NOTE :
- $F_w$  is the myometer reading in newtons.
  - $F_e$  is the force exerted against the machine in newtons.
  - $L_e$  is the lever arm from the machine centre of rotation to the centre of the hand-grip bar
  - $h$  is the distance from the centre of the shoulder joint to the machines centre of rotation
  - $x$  is the distance from the centre of the shoulder joint to the centre of the hand-grip bar
  - $e_a$  is the perpendicular distance from the centre of the shoulder joint to the line of the force ( $F_e$ )
  - $r$  is the radius from the centre of the machines rotation to the cable

FIGURE 25: Derivation of the equations to calculate musculo-skeletal torque on the 'pullover' machine.

through its range. The design of eccentric cams was developed in an attempt to vary the resistance experienced by the working muscle through its range of motion. The cam serves as an efficient fulcrum when the musculo-skeletal lever is inefficient and vice versa. The desired effect is to maintain constant tension in the working muscle(s) at all points through its range.

Thus the object of ergonomic re-design is to match the mechanical requirements of the machine with the biomechanical characteristics of the human musculo-skeletal system; in other words to ensure that the torque required by the machine changes at the same rate and in the same direction (increase or decrease) as the torque exerted by the user through the range of motion.

The relevant levers required to derive equations required for determining musculo-skeletal torque, and consequently the redesigned cam radii are shown in Figure 1. In order to achieve equilibrium it is necessary to exactly counterbalance the resistive and effort moments on the 'pullover' unit. Therefore:

$$F_w \cdot r = F_e \cdot L_e \dots\dots\dots \text{So: } F_e = F_w \cdot \frac{r}{L_e} \quad (1)$$

In establishing the equation for musculo-skeletal torque ( $T_m$ ), it is necessary to determine the product of the force and the moment arm (perpendicular distance from the line of force to the axis). However, Figure 1 shows that the moment arm (ea) has to be calculated since the distance from the centre of the shoulder to the centre of the grip is not at right angles to

the force ( $F_e$ ). This was done by applying Pythagoras' Theorem where:

$$ea^2 = x^2 - h^2 \dots\dots\dots \text{So: } ea = \sqrt{x^2 - h^2}$$

NOTE: 'h' remains constant, while 'x' varies through the range of motion (on the assumption that the joint angles at the elbow and wrist remain constant).

Therefore, the equation of moment equilibrium for muscle torque on the 'pullover' unit is:

$$T_m = F_e \cdot ea \quad (2)$$

However, (1) and (2) have different fulcra of balance.

Thus, from (1):  $F_e = F_w \cdot \frac{r}{L_e}$

So:  $T_m = F_w \cdot \frac{r}{L_e} \cdot ea$

Tests of the cam radius were conducted at 4 isometric positions of shoulder flexion (20°, 60°, 100°, 135°).

Figure 26 shows the pattern of musculo-skeletal torque generated by a mixed-sex group of active young adults, without upper-extremity clinical histories. Figure 27 depicts the cam radii required to ensure that maximal muscle force is generated throughout the range of motion, and the cam radii presently installed, which fail to achieve that purpose. Re-designed cam radii are presented in Table IX and the redrawn cam shape in Figure 28.

A present design weakness of the 'pullover' machine under analysis was found in the initial starting position: users had to turn their heads in order to look back to see where the bar

was before grasping it. Once the bar had been grasped, the user tended to be seated with the back in hyperextension. This produced two repercussions. Firstly, undue stress was placed on the spine as the grasp was made causing user discomfort, and secondly the initial movement of the bar was accompanied by a contraction of the abdominal muscles in order to straighten the back. This hyperextension and use of the abdominal muscles was repeated every time the bar returned to the starting position during a set of repetitions.

Musculo-skeletal analysis of the "pullover" exercise showed that elbow flexion and wrist extension changed through the range of motion. It was noted that the excess stretch caused by the initial starting position resulted in small users raising the seat to establish optimal comfort, producing greater flexion of the elbows. The altered wrist and elbow angles through the range of motion were due purely to the fact that the machine's fulcrum was not the same as that of the user. Figure 29 shows that because the machine's fulcrum was behind that of the user, the user's arc was smaller than that of the machine. In order to accommodate for this, users had to adaptively flex and extend the elbows and wrists.

Figure 30 shows suggested design alterations for the 'pullover' machine. The main suggestion for re-design was that the machine's fulcrum be placed anterior to the back rest.

This has two effects. Firstly, the back-rest would now be in posterior to the cross-bar, thereby reducing the initial

**TABLE IX:** Mean isometric vertical shoulder extension force, derived torque and associated positional and machine specification factors, for a combined-sex group of active young adults.

Parameter	Data				Derivation
	20° Start	60°	100°	135° Finish	
Degrees of Flexion					(Measured)
Cam Radius (m)	0.197	0.208	0.233	0.249	(Measured)
Myometer ( $F_w$ ) (N)	1018	1143	867	633	(Recorded)
Torque ( $T_m$ ) (Nm)	165.6	162.0	116.4	101.3	( $F_w \cdot r_{ea}/LE$ )
Force exerted Against Machine ( $F_e$ ) (N)	342.3	399.7	339.6	265.7	( $F_w \cdot r/LE$ )
Adjusted Cam Radius (M)	0.280	0.274	0.197	0.171	(Based on 0.171 set at 135°)
Adjusted $F_w$ (N)	591.4	591.2	590.9	592.4	( $T_M \div$ adjusted cam)

stretch required at the beginning of the exercise. Isolated stress of the musculature utilised in pure shoulder extension is best achieved by performing the exercise with extended elbows. Therefore, by having the machine's fulcrum in front of the back rest and in line with that of the users' fulcrum, there should be no changing elbow flexion and wrist extension during the exercise and all musculature associated with this elbow flexion and wrist extension would no longer be utilised.

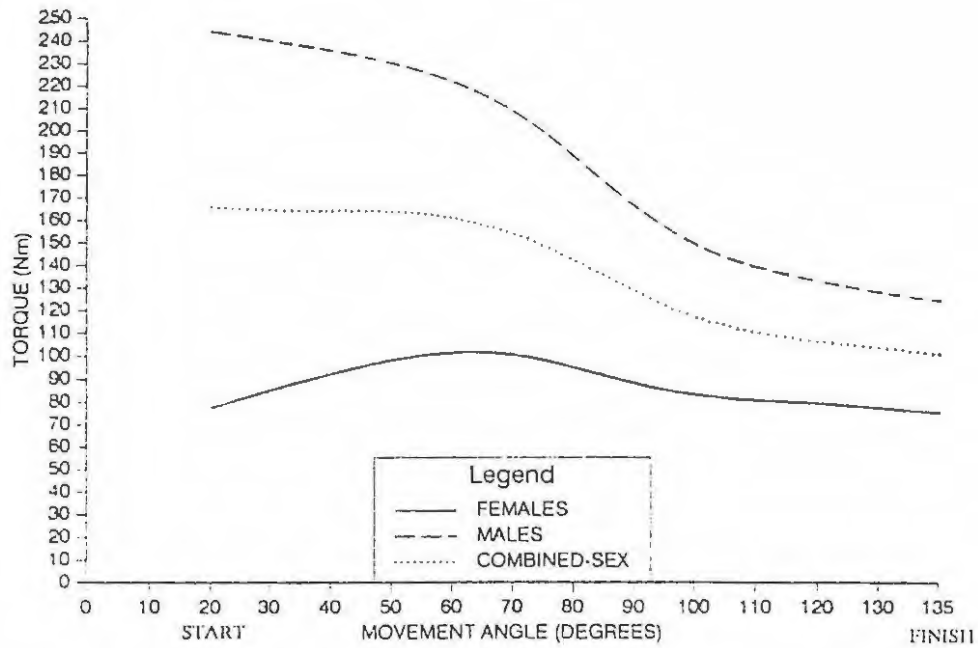


FIGURE 26: Combined-sex muscle torque curves plotted from isometric maxima at 20°; 60°; 100°, 135° of vertical shoulder extension.

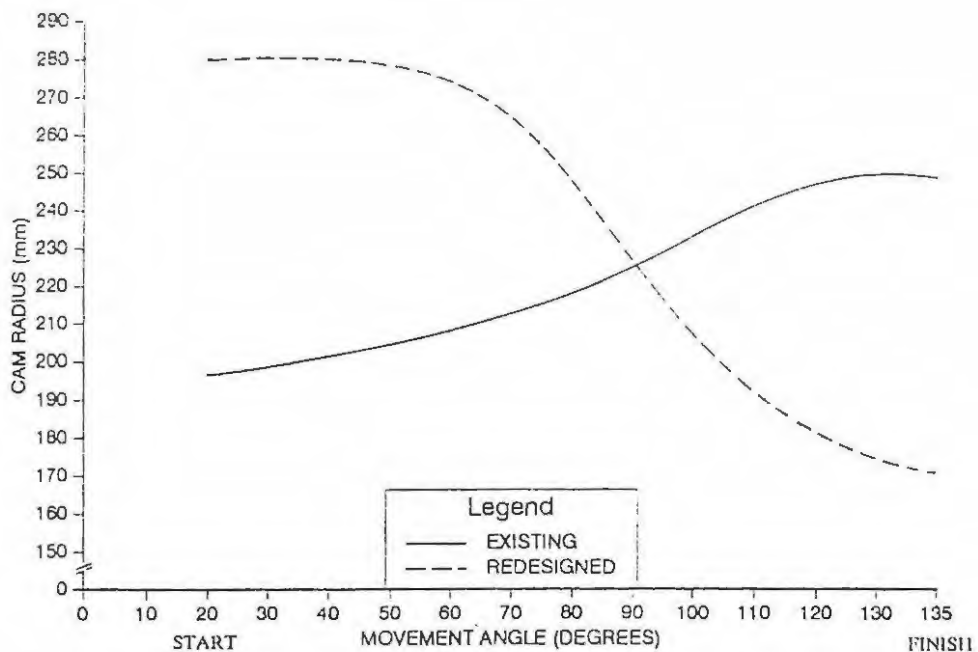


FIGURE 27: Existing and re-designed eccentric cam radii to show the need for improvement on the 'pullover' unit.

When the seat is placed in the central setting, the distance from the seat to the fulcrum has been increased to 83 cm. This measurement is roughly about the mean sitting shoulder height for black and caucasian South African male populations at the 50th percentile. Therefore, in order to keep machine and user fulcra the same, shorter people have to raise the seat, and in contrast taller people have to lower it.

The distance from the cross-bar to the machine's fulcrum should also be increased in an attempt to keep the arms as straight as possible throughout the exercise. If the arms cannot be completely straight, there should be no change in the wrist and elbow angles through the range. Shoulder extension should ideally be carried out through 180°. At present the range of motion of the machine is about 135°. This range is further limited by the fact that when the feet are placed on the foot rest, the flexed knees protrude above the level of the seat, the bar stopping when it comes up against the thighs. In contrast, shorter people have to raise the seat to such an extent that they cannot reach the foot rest.

It is suggested that the exercise be performed with the feet on the floor, and the user in a more upright standing position. Consequently the seat's support bar has been raised above the base of the machine. Thus, by placing the feet on the floor hip flexion would be decreased, increasing the range of motion. This modification, if adopted, would require some alteration of the seat design to allow the legs to splay on either side of the seat.

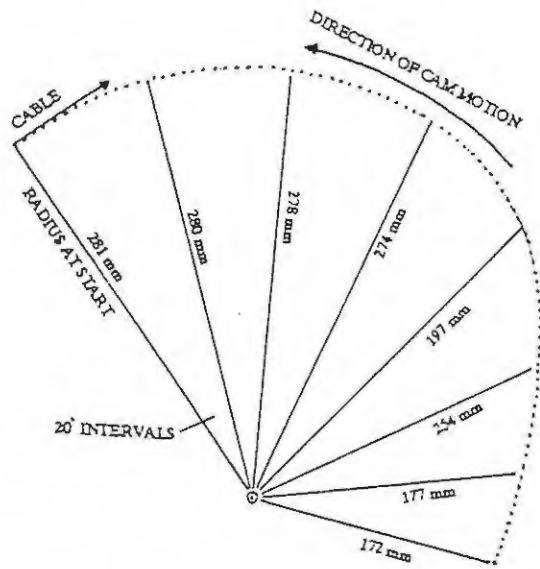


FIGURE 28: Redesigned cam shape based on radii given in Table IX and Figure 27 for the 'pullover' machine.

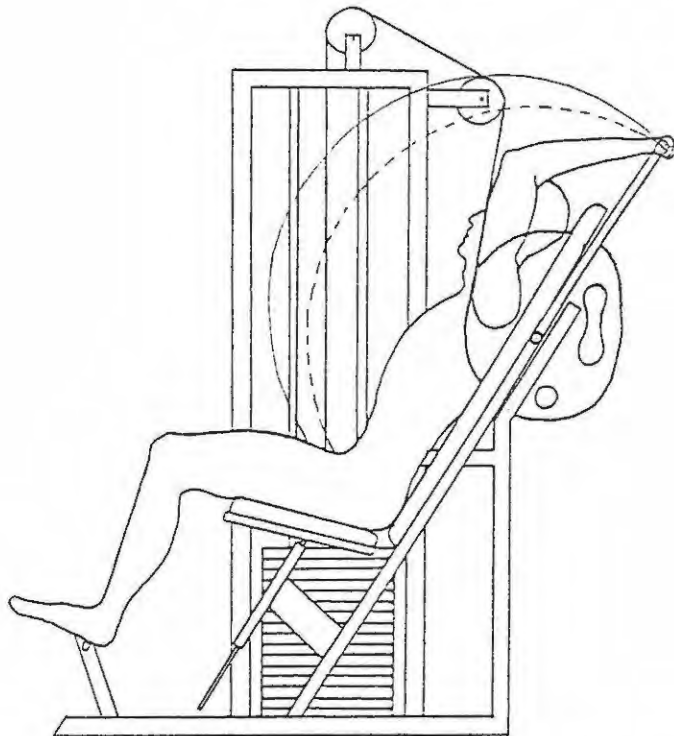


FIGURE 29: Showing that the cross-bar arc of the 'pullover' machine ( --- ) is smaller than that of the 'user' ( ——— ), causing flexion of the elbow and wrist to compensate for the arc difference.

It was suggested that a 'pullover' machine utilising upper-arm pads rather than a hand-grip bar would provide a more beneficial exercise effect for the shoulder extension musculature, for a number of reasons. Firstly, the elbow pads would allow a greater range of motion (greater than  $180^\circ$ ) thereby accessing more of the related musculature. Secondly they would also permit unilateral use, with implications for sports training and injury rehabilitation. Thirdly, the pads would mean that individuals who are too weak to grasp the bar for reason of incapacity distal to the shoulder would still be able to perform this exercise. It is, however, suggested that the re-design characteristics of the cross-bar machine be implemented. Tests showed that stronger young adult males could handle more weight than the weight stack presently provides. This was not a major draw-back, however, and is merely for noting. Increasing the range of motion beyond the present  $140^\circ$  limit would reduce this deficiency.

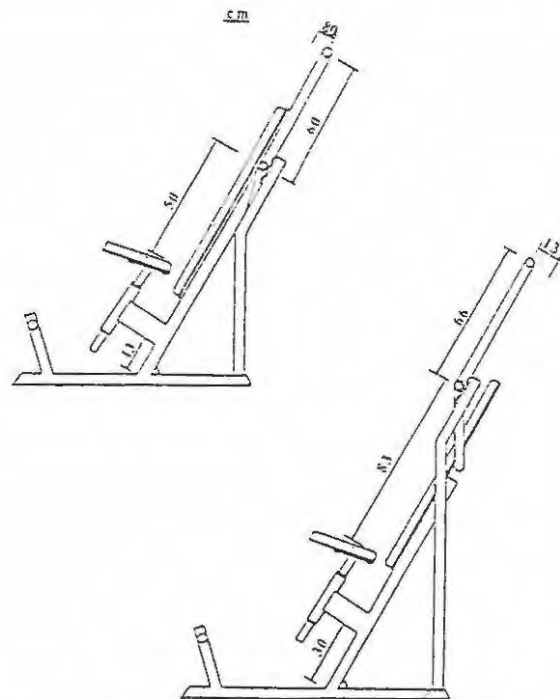


FIGURE 30: Suggested design alterations for the 'pullover' machine.

## SECTION 2 : MUSCULO-SKELETAL ANALYSIS

### 2.1 Isometric Torque Maxima

Table IX summarises the combined-sex maximal isometric force and torque data of a group of healthy, active young adults of both sexes at four selected positions through the range of motion. Isometric maxima varied in parallel through the range of motion for males and females, although males were consistently significantly stronger (See Figure 31). Consequently no substantive sex-related design modifications were needed, and any adjustable features of the machine would be justified on the basis of body-size, not sex *per se*.

### 2.2 Relevant Muscles of the Shoulder Joint, Shoulder Girdle, Elbow and Wrist.

The muscles primarily involved in shoulder extension against resistance are the lower fibres of the pectoralis major, latissimus dorsi and teres major. The posterior fibres of the deltoid and the long head of the triceps brachii also contract concentrically to cause shoulder extension against resistance. The contralateral muscles are the anterior deltoid and upper fibres of the pectoralis major. Other muscles employed in shoulder extension are coracobrachialis, serratus anterior and, as fixators, rectus abdominis. The guiding muscles in shoulder extension lie parallel to the anteroposterior plane of motion. These are the medial and lateral rotators, namely infraspinatus, teres minor, subscapularis, long head of biceps brachii and the scapular

fibres of deltoid.

Due to the design of the 'pullover' machine not only are the muscles of shoulder extension utilised in this exercise, but so too are the muscles active in elbow flexion: biceps brachii, brachialis, brachioradialis, extensor radialis longus and pronator teres - and in wrist extension - extensor digitorum, extensor carpi radialis brevis, extensor indicis and extensor pollicis longus (See Figure 33).

Figure 32 shows that for tall people, elbow flexion on this unit increases until approximately 90 to 100° of the range of motion, whereupon it begins to decrease. Elbow flexion is greater at the end of the exercise than at the beginning of the exercise for taller people. In contrast, shorter people reach the greatest elbow flexion at about 60° through the range of motion, after which it decreases, so that it is less at the end of the exercise than at the initial position.

Figure 32 indicates that wrist extension increased through the range. Males and females responded similarly, the degree of wrist extension varying in parallel through the range, with females having slightly greater wrist flexion than males. It was noted that in some instances, males started the exercise with the wrists in flexion which had become wrist hyperextension by the end of the exercise.

These changes in wrist and elbow angles affect the musculature utilised through the range of motion.

Figure 33a shows that at the beginning of the exercise, the primary musculature involved is that of shoulder extension: latissimus dorsi, teres major, pectoralis major and posterior

deltoid. As elbow flexion and wrist flexion increase (Figure 33b), the musculature of these two movements becomes more prominent, with shoulder extension musculature predominantly used.

By the position shown in Figure 33c, the movement of the bar is being brought about, to a greater extent, by elbow and wrist flexors, than by the shoulder extension musculature. By the final position indicated in Figure 33d, the movement of the bar towards the thighs is caused more by extension of the elbow joint, especially in shorter people, rather than by retroversion of the humerus caused by the musculature of the back.

Consequently, muscles not associated with true shoulder extension are employed in the use of the present "pullover" unit. This is further complicated by the effect of hand position on the musculature during the exercise. The wider apart the hands are, the greater the emphasis placed on the adductor and medial rotating musculature.

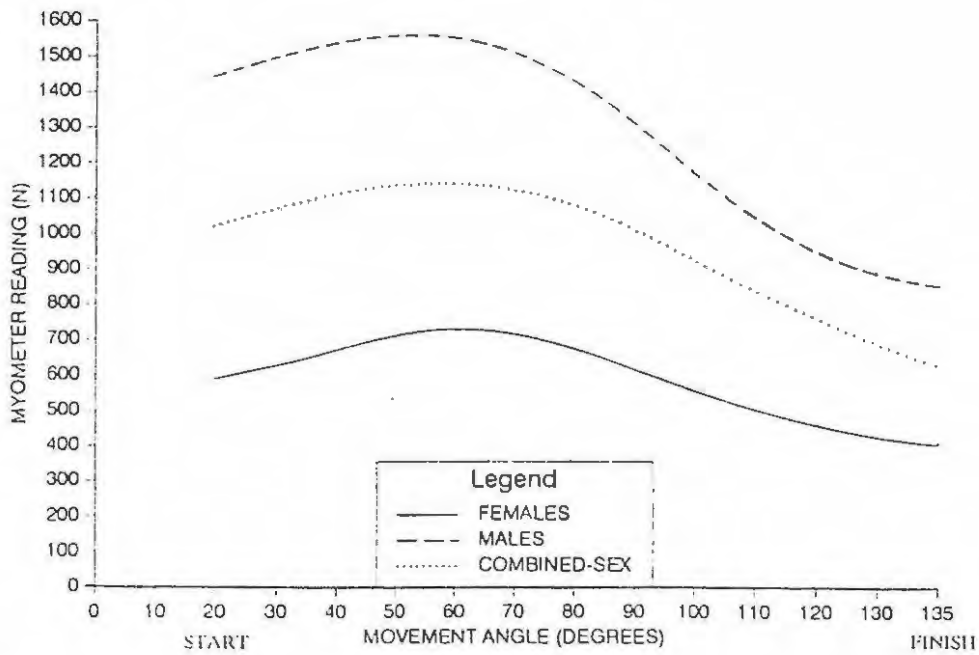


FIGURE 31: Sex-based and combined-sex differences in isometric maxima produced at four test-points through the range of vertical shoulder extension.

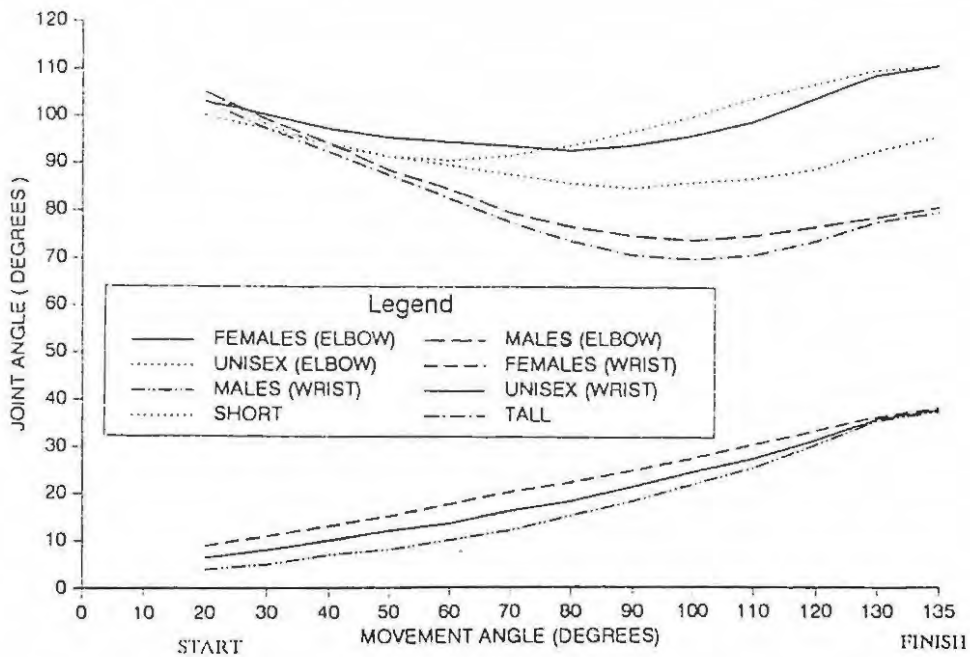


FIGURE 32: Degrees of elbow and wrist extension through the range of motion of vertical shoulder extension.

Musculature utilised during shoulder extension:

Extensor Digitorum  
 Brachioradialis  
 Brachialis  
 Biceps Brachii  
 Triceps Brachii  
 Teres Major  
 Latissimus Dorsi  
 Posterior Deltoid

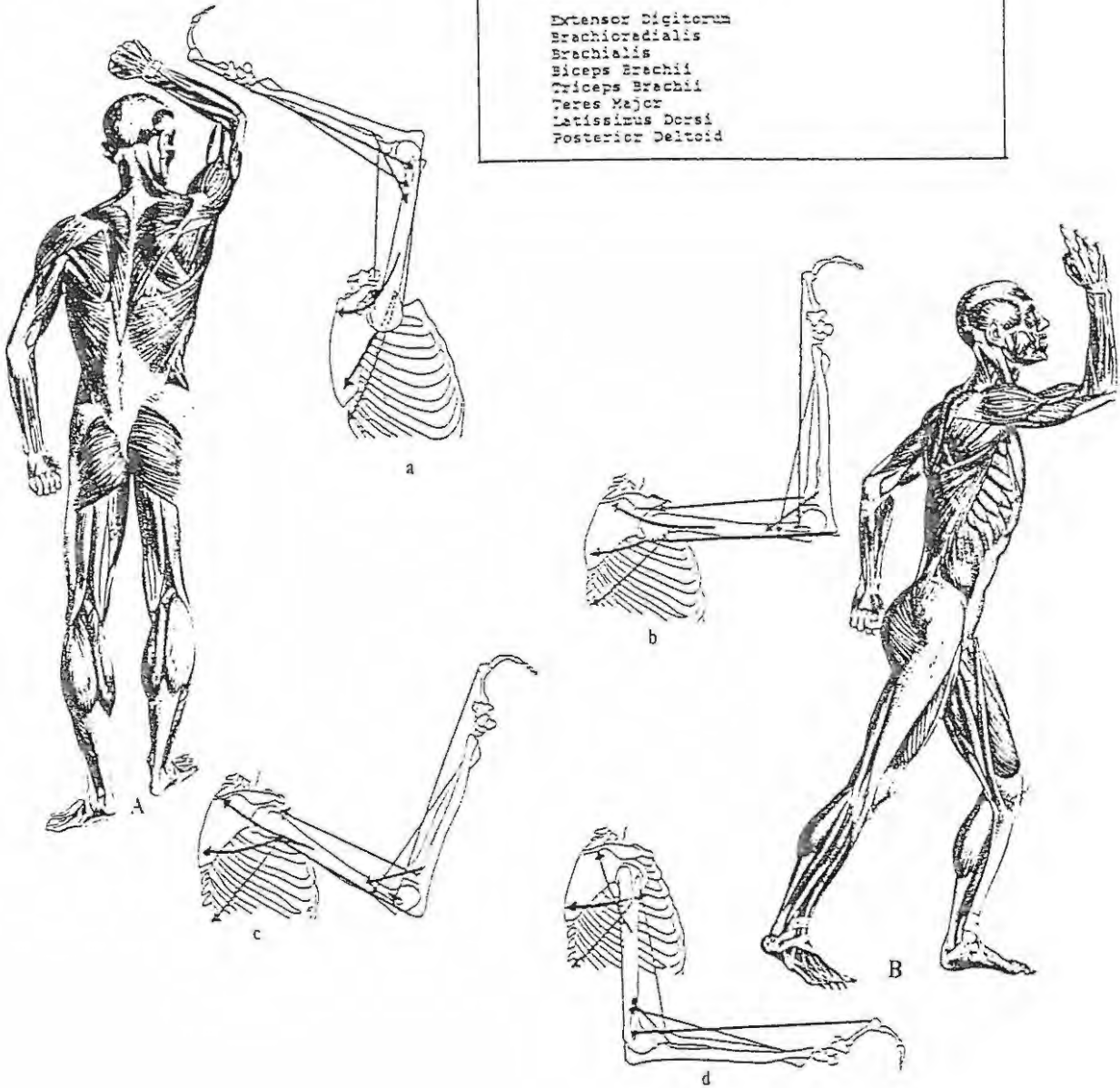


FIGURE 33: Musculature utilised in the 'pullover' movement (A) and (B), and the extent of musculature involved in elbow and wrist flexion through the range of motion of elbow extension on the 'pullover' unit.

### SECTION 3 : METABOLIC ANALYSIS

This analysis comprised a sex-based energy-cost assessment made at selected submaximal isoinertial lift intensities. Subjects were required to perform fixed-rate lifts at two different effort levels: 10% and 30% of maximal lift-specific muscle capacity set for each individual.

The lift-rate was set by a metronome at 25 reps.min<sup>-1</sup> and subjects were required to exercise continuously at this rate for 10 min. at each of the pre-selected intensities; 10% and 30% stress levels. In addition, breathing patterns were monitored, and as far as was possible, were fixed in accordance with standard practice at the pre-set cadence while ventilating through a portable oxygen meter (See Chapter 3).

A summary of the findings of the metabolic analysis is given in Table X. Reference to Figure 34 illustrates that for males and females the oxygen cost of the work done at both intensities (10% and 30% stress levels) is negligible. In fact, even in the most strenuous condition (Male 30% stress level), the metabolic equivalent (MET) is only 2.84 times that at rest. In terms of any classification of work intensity this is "light" work.

Even with relatively sophisticated metabolic analysis technology quantification of the anaerobic component of the total energy demand is difficult. In the present study it was impossible, but by using the psychophysical data (see Section 4) some indications of the extent to which local (muscular) and central (cardiovascular) cues predominated were gained. At the 10% stress level males and females perceived the effort

required very similarly, both in terms of central and local cues.

This suggests that perhaps the low metabolic cost obtained (Figure 35) is load-dependent and also due to the relatively small musculature utilised in this exercise. At a 10% stress level the load moved was 7.5 kg (lightest) for females and 15 kg for males. In contrast, at 30% stress level, "local" RPE were higher than the "central" RPE for males and females. This, combined with the low metabolic costs, suggests that anaerobic energy production is being utilised at 30% stress level, which is typical of activities in which muscular strength rather than aerobic power predominates. Therefore, it appears that at the 30% stress level, there was some contribution to the total energy demand from aerobic sources, but most was produced anaerobically.

Figure 35 indicates that for males and females at 10% and 30% stress levels for females, there is little difference between mean metabolic cost at each effort-level, while at the 30% stress level for males, the mean metabolic cost is almost twice the other three effort-levels. Table XI shows that at equivalent relative loads, energy expenditure for females was 0.93 and 0.61 of the males under 10% and 30% stress respectively. Clearly it is absolute load and not relative load which determines energy expenditure.

From these results, the 'pullover' unit appears to allow one to develop muscular strength and/or muscular endurance. Both are predominantly anaerobic activities, and therefore in terms of a training response, only the anaerobic metabolic

pathways would be stressed significantly. This is shown by the fact that at the lowest resistance (7.5 kg) moved at 25 rpm for 10 min a metabolic cost of only  $0.5\ell \text{ O}_2 \cdot \text{min}^{-1}$  was incurred; this is also largely a function of the relatively small proportion of the total musculature utilised to perform the movement. These data tend to suggest that this is not a weight-losing device, but primarily a muscle building device.

TABLE X : Mean metabolic response to work on the 'pullover' machine at 10% and 30% max (Standard deviations in brackets).

	10% Max		30% Max	
	Male	Female	Male	Female
Relative Load (kg)	15.0 (0.00)	7.5 (0.00)	37.5 (0.00)	22.5 (0.00)
$\text{VO}_2$ ( $\ell \cdot \text{min}^{-1}$ )	0.54 (0.01)	0.5 (0.03)	0.83 (0.06)	0.51 (0.03)
$\text{VO}_2$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	6.37 (0.86)	9.27 (0.52)	9.93 (1.17)	9.04 (1.04)
METS	1.82 (0.24)	2.65 (0.17)	2.84 (0.30)	2.58 (0.30)
$\text{kcal} \cdot \text{min}^{-1}$	2.68 (0.50)	2.5 (0.3)	4.13 (0.3)	2.53 (0.6)
$\text{V}_e$ ( $\ell \cdot \text{min}^{-1}$ )	16.1 (3.91)	16.28 (1.61)	25.0 (2.45)	18.2 (3.50)

NOTE: Mean male max (1 RM) was 112.5 kg (SD 0.00)  
Mean female max (1 RM) was 65.63 kg (SD 7.18)

TABLE XI: Female data, in percentage of male data (100.F/M) on the 'pullover' unit.

	Stress Level	
	10% Max	30% Max
VO <sub>2</sub> (ℓ.min <sup>-1</sup> )%	92.6	61.4
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )%	145.5	91.0
METS %	145.6	90.8
kcal.min <sup>-1</sup> %	93.3	61.3
V <sub>e</sub> (ℓ.min <sup>-1</sup> )%	101.1	72.8

Table XI summarises the relative performance of the females in the sample. The female loads constitute 58% of the male loads under maximal conditions, 60% at 30% max and 50% at 10% max. Females tend to be about 70% as strong as males, with a range of 59-84% depending on the muscle groups tested (McArdle et al., 1991). It must be noted, however, that the males 1 RM was machine limited. That is, all the subjects could lift the entire weight stack (112.5 kg), but this was not necessarily their 1 RM. In contrast the female subjects all lifted their 1 RM before reaching machine capacity.

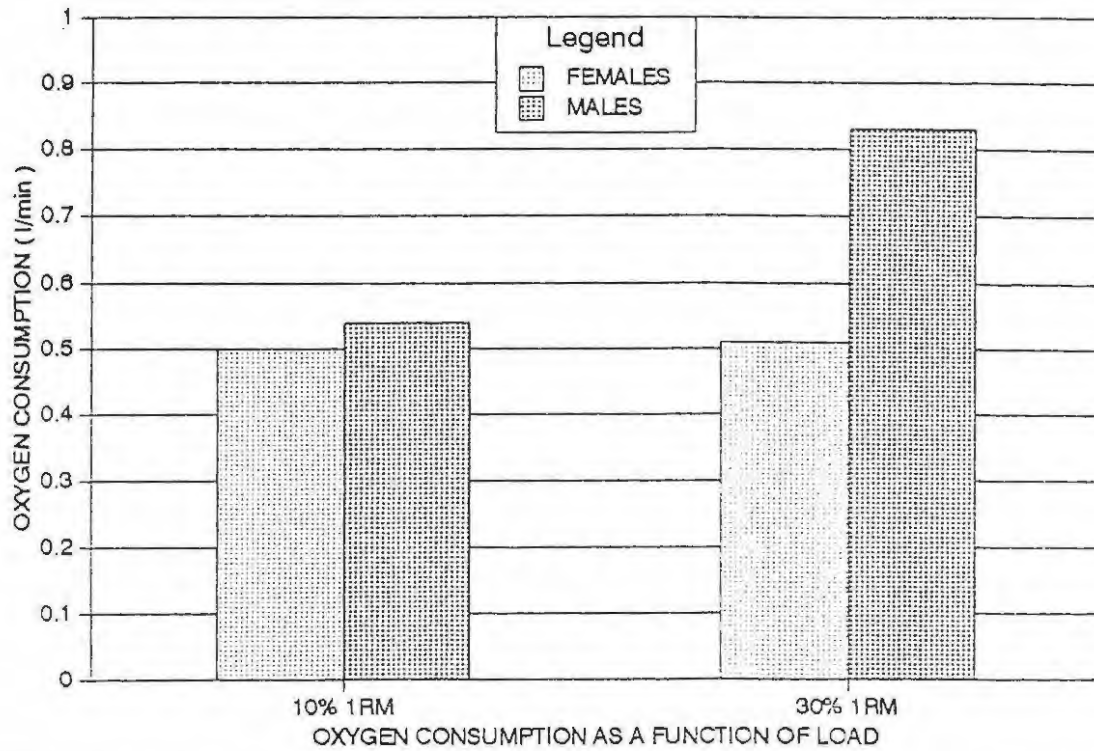


FIGURE 34: Showing average  $O_2$  consumption for each 10 minute period at 10% and 30% stress levels for males and females on the 'pullover' unit.

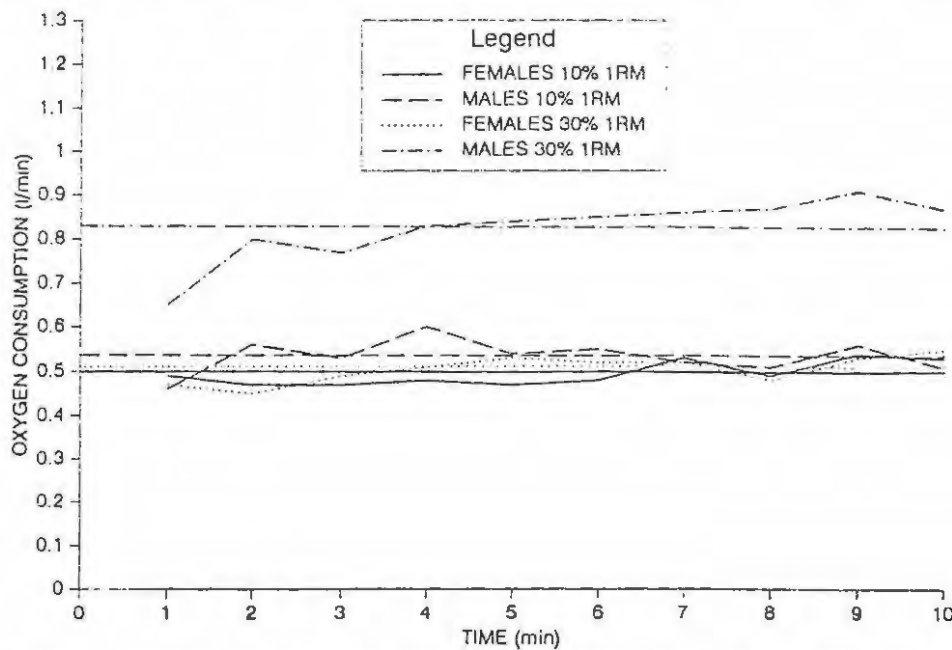


FIGURE 35: Average oxygen consumption ( $l \cdot min^{-1}$ ) at 10% and 30% stress levels for males and females (Dotted lines indicate means), for 10 minutes of exercise on the 'pullover' unit.

#### SECTION 4 : PSYCHOPHYSICAL ANALYSIS

Table X shows that the absolute loads at 10% and 30% stress levels are quite different for males and females; males always moving heavier absolute loads than females at the same relative load. Figure 36 shows that, in spite of the absolute load difference between sexes, the mean ratings of perceived exertion (RPE) for the 10 min. exercise duration are quite similar at each relative load.

At 10% stress level the mean rating of perceived exertion for the muscles involved was "very, very light" for males and "very light" for females. Mean cardiovascular ("central") RPE for males was "very, very light", while for females this rating was "very light".

At 30% stress level the males mean rating for "local" RPE for the 10 min. period was "somewhat hard", while the females mean rating was "fairly light". In contrast, mean "central" ratings for males was "fairly light", and for females the mean rating was "very light".

At 10% stress level the mean RPE values for "local" RPE do not appear to be very different from the mean "central" values. This is probably due to the very light load moved during the 10 min. exercise period. In contrast, at 30% stress level, the mean "local" RPE values appear to be slightly higher than the mean "central" values. This reflects a higher intensity of work than is indicated by either  $O_2$  consumption ( $l \cdot \text{min}^{-1}$ ) or derived energy expenditure ( $\text{kcal} \cdot \text{min}^{-1}$ ) at the same relative loads

(Table X). This tends to indicate anaerobic stimuli producing much of the input for perceptions of exertion at 30% max, in this type and duration of activity.

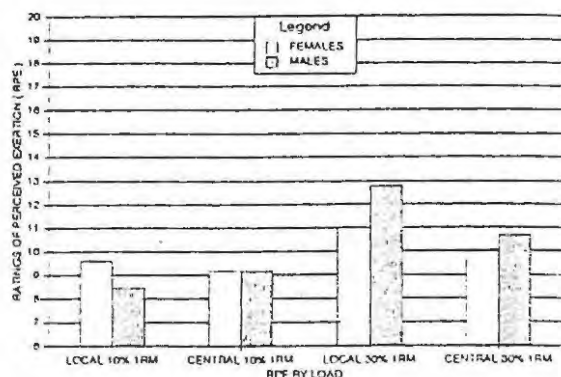


FIGURE 36 : Ratings of perceived exertion (RPE) and load on the 'pullover' unit.

#### SUMMARY

The seat support was raised in order to provide a greater range of motion. The machine's fulcrum was moved anteriorly to the back rest, in line with that of the user. The machine's lever arm was lengthened to reduce influence of other musculature other than that required for vertical shoulder extension. Despite working continuously for 10 min the metabolic cost at 10% and 30% stress is clarified as light, as indicated by perceptual responses. It appears that only at the 30% stress level do 'local' cues begin to dominate.

Therefore on the 'pullover' unit it was concluded that, even moving the lightest load for 10 min did not induce a noticeable increase in metabolic cost above resting levels. Therefore the 'pullover' unit should be used for muscular endurance and/or strength development.

## ANALYSIS FOUR : TRUNK FLEXION UNIT

### INTRODUCTION

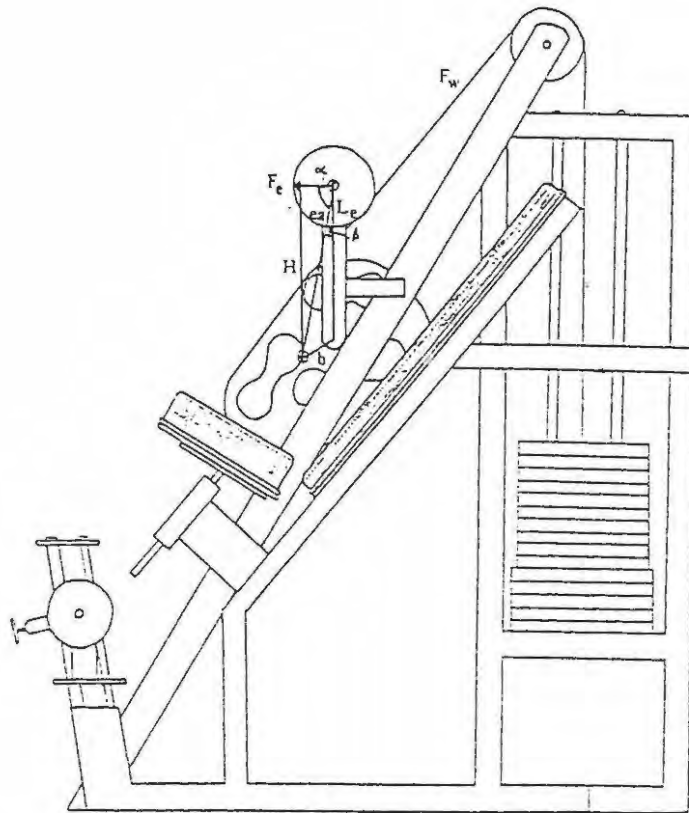
This machine permits seated spinal extension-flexion through a range of approximately 95°. The seating arrangement and position of the chest pad are such as to provide a position-controlled isoinertial vertical lift of adjustable loads, by arc motion of the torso about the pelvis.

The design aims to standardise operator position comfortably and safely so that load adjustments commensurate with increases in strength can easily be reset. The adjustable foot rest allows a training effect to be effected on either some or all of the abdominal musculature.

The range of motion, step increments of the weights and the adjustable seat height and foot rest indicate a design intended to accommodate users of diverse levels of strength and body size.

### SECTION 1 : ENGINEERING ANALYSIS

The object of ergonomic re-design is to match the mechanical requirements of the machine with the biomechanical characteristics of the human musculo-skeletal system; in other words to ensure that the torque required by the machine changes at the same rate and in the same direction (increase or decrease) as the torque exerted by the user through the range of motion, i.e.  $F_e \cdot L_e = F_w \cdot r$  (See Figure 37).



- NOTE:       $ea$  is the distance from the top of the iliac crest to the centre of the chest pad
- :       $b$  is the distance from the top of the iliac crest to the machines centre of rotation.
- :       $L_e$  is the distance of the machines lever arm from the centre of rotation to the centre of the chest pad.
- :       $F_e$  is the force exerted against the machine in newtons
- :       $F_w$  is the myometer reading in newtons
- :       $H$  is the calculated distance from the iliac crest and perpendicular to the force exerted  $F_e$
- :       $\beta$  is the calculated angle between  $L_e$  and  $ea$
- :       $\alpha$  is the angle used to determine  $H$

Figure 37: Derivation of the equations used to calculate muscle torque on the 'abdominal' machine.

Thus, the presenting problem which needs to be solved in this, and all such equipment, is to design an accommodating resistance system to adapt to changes in musculo-skeletal leverage through the normal range of motion of the joint in question. When a muscle contracts dynamically against isoinertial resistance, the tension produced in the muscles increases or decreases as the muscle lengthens or shortens through the range. Eccentric cams were developed in an attempt to ensure maximum tension throughout the range, rather than at one single "weak-point" on the strength curve of the muscle. Therefore the cam serves as an efficient fulcrum when the musculo-skeletal lever is inefficient and vice versa.

In order to determine musculo-skeletal torque ( $T_m$ ) it was necessary to determine the product of the force (effort or resistance) and the moment arm at a perpendicular distance from the line of force to the axis. Figure 37 shows that this perpendicular distance 'H' had to be derived since the distance ea was not at right angles to the force  $F_e$ .

Since the lever arm  $L_e$ , the distance b and ea were known it was possible to determine the angle B as follows:

$$\beta = \text{arc Cos } \frac{L_e^2 + ea^2 - b^2}{2.L_e.ea}$$

Having calculated  $\beta$ ,  $\alpha = 90^\circ - \beta$ . Since it is H which must be determined, simple trigonometry dictates that:

$$H = ea. \text{ Sin } \alpha$$

and therefore:

$$T_m = H.F_e \quad (1)$$

In counterbalancing the effort and resistive moments to achieve equilibrium on the abdominal unit:

$$F_w \cdot r = F_a \cdot L_a \dots \dots \dots \text{So: } F_a = \frac{r}{L_a}$$

However (1) and (2) have different fulcra of balance.

$$\text{From (1) } F_a = F_w \cdot \frac{r}{L_a} \dots \dots \dots \text{So: } T_m = F_w \cdot \frac{r}{L_a} \cdot H$$

Tests of the cam radius were conducted initially at four isometric positions of spinal flexion (15°; 45°; 70°; 90°). A group of young adults without clinical spinal histories was tested in the above four positions. Data for both sexes were pooled since the design must cater for all users. Figure 38 shows the changing pattern of musculo-skeletal torque. Figure 39 depicts the cam radii required to ensure that maximal muscle force is produced throughout the range of motion, and the cam radii presently installed, which fail to achieve that purpose. Redesigned cam radii are presented in Table XI, while Figure 40 shows the redesigned cam shape.

The major weakness of the abdominal machine studied is the initial starting position of the chest pad. It appears that, in its present position, users have to perform a certain degree of spinal flexion before encountering any resistance (see Figure 41). This initial degree of flexion varies from individual to individual depending on chest depth. The length to which a muscle is stretched before contracting has

considerable effect upon the subsequent force of contraction, such that maximum force is achieved when the stretch is 20-30% above the muscles' normal resting length (Klausen, 1988). Further increases or decreases (as is this case with the present design) in pre-contraction length result in sub-optimal force outputs.

Figure 42 shows the design modifications suggested to ensure maximal force possible on the abdominal unit. The starting angle of the lever arm and chest pad have been altered such that the chest pad is now closer to the back rest. The new starting position of the chest pad is based on an average chest depth of approximately 25 cm. However, in order to accommodate differing chest depths, it is suggested that a facility similar to that employed on the 'knee extensor' unit is utilised. That is, a pegging mechanism allowing the starting position of the chest pad to be altered according to various chest sizes.

This pinning facility has a further possible use. When the thighs and torso are at right angles, and the abdominal muscles are contracted, it is the upper portion of the abdominal muscles which is stressed. This is the basis of the curled sit-up. As the angle between the thigh and torso becomes increasingly more obtuse, more of the abdominal musculature is employed. On the present abdominal unit this greater obtuse angle is attained by lowering the adjustable foot rest. Therefore, if the pinning facility is implemented,

an individual who wishes to stress only the lower portion of the abdominal muscles may pin the chest pad in the required starting position, lower the foot rest, and complete the exercise.

A complaint noted by many users of the abdominal unit, especially women, is that as the exercise is carried out, the chest pad tends to 'roll' down the chest. This is the result of the machine's lever arm ( $L_e$ ) being shorter than the effort arm ( $ea$ ) of the user. Consequently, Figure 45 indicates that the lever arm has been lengthened to 360mm. This measurement is based on the approximate distance from the top of the thigh to the top of the shoulder when in a seated position based on an adult of average stature. This should leave the top of the chest pad at the height of the manubrium of an individual's chest. Some abdominal machines implement a flat chest pad to prevent the "rolling" action. However, the increase in  $L_e$  means that there should be very little "rolling" action, and any "rolling" present should cause little discomfort.

**TABLE XII:** Mean isometric spinal flexion force, derived torque and associated positional and machine specification factors, for a combined-sex group of young adults.

PARAMETER	DATA				DERIVATION
	15° START	45°	70°	90° FINISH	
Degrees of Flexion					(measured)
Cam radius (m)	0.178	0.194	0.204	0.199	(measured)
Myometer ( $F_w$ ) (N)	523.1	569.7	708.1	682.8	(recorded)
Torque ( $T_m$ ) (Nm)	100.71	114.80	112.17	91.78	( $F_w \cdot r / L_e \cdot H$ )
Force exerted against machine ( $F_e$ ) (N)	338.6	431.9	525.3	494.1	( $F_e = r / L_e$ )
Adjusted Cam radius (m)	0.218	0.249	0.243	0.199	(based on 0.199m set at 90°)
Adjusted $F_w$ (N)	461.9	461.04	461.60	461.21	( $T_m \div$ adj cam)

A further cause of discomfort is the shape of the seat. The seat was designed to allow the legs to splay to either side, thereby increasing the range of motion. However, at present, this set-up is not as comfortable as it might be. It is suggested that the seat design used be substituted by a flat "triangular" shape, which would still allow splaying of the legs, while ensuring user comfort.

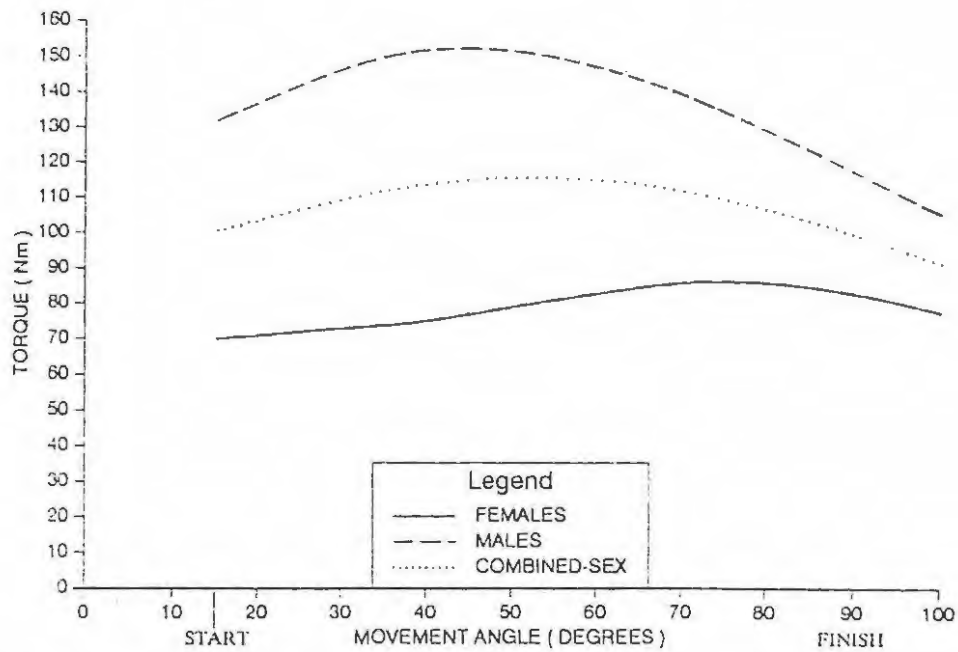


Figure 38: Sex-based and combined sex muscle torques plotted from isometric maxima at 15°, 45°, 70° and 90° on the 'abdominal' unit.

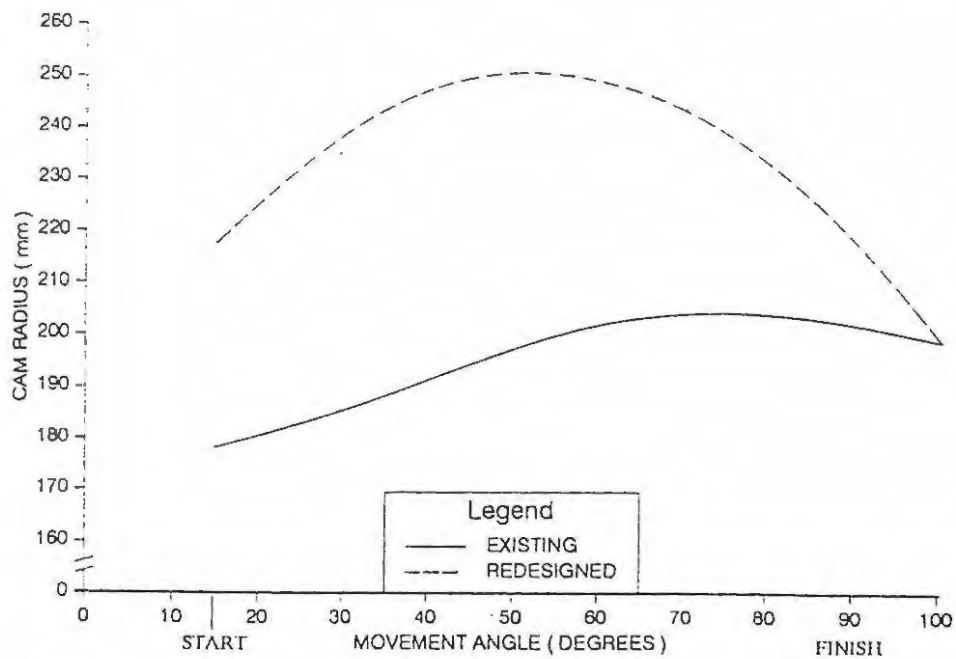
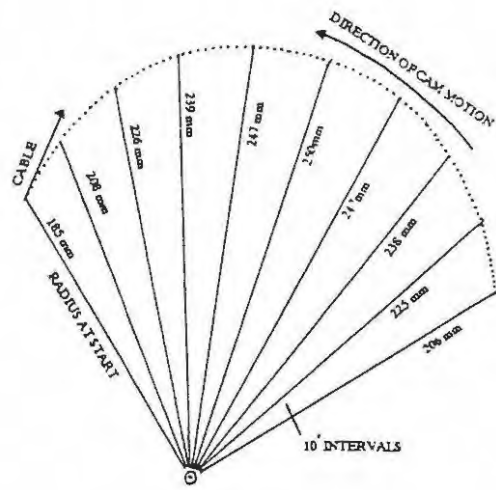


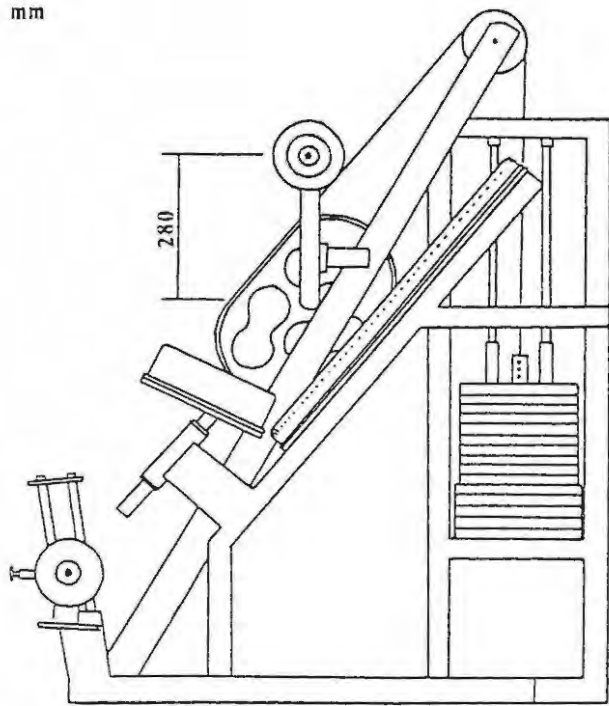
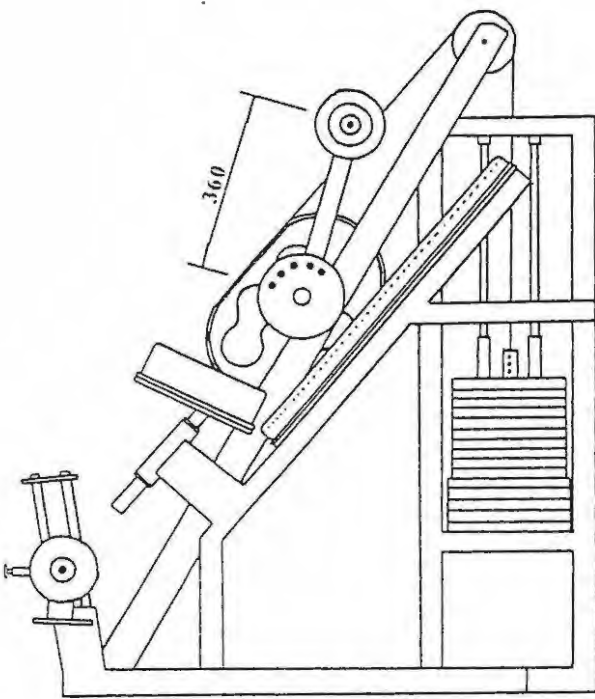
Figure 39: Existing and re-designed eccentric cam radii showing the need for improvement on the 'abdominal' unit.



**FIGURE 40:** Redesigned cam shape for the 'abdominal' unit based on radii given in Table XII and Figure 39.



**FIGURE 41:** Photograph showing initial spinal flexion required before encountering resistance.



**Figure 42:** Redesigned lever arm and pinning mechanism allowing differing starting positions on the 'abdominal' unit.

## SECTION 2 : MUSCULO-SKELETAL ANALYSIS

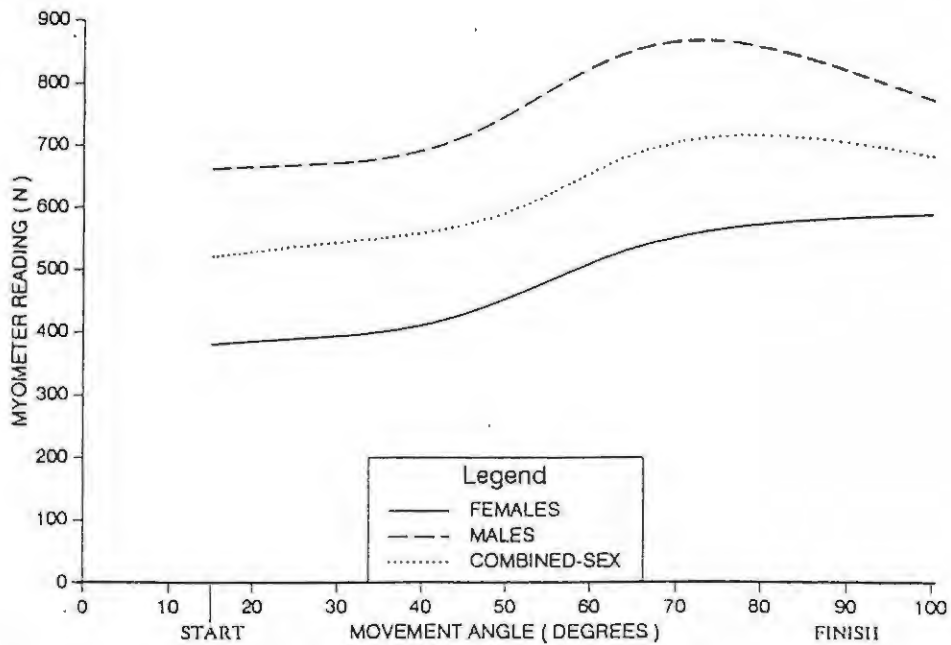
### 2.1 Isometric Torque Maxima

Summarised combined-sex maximal isometric force and torque data of a healthy active young group of adults at four selected positions through the range of motion, are presented in Table XII. Males and females isometric maxima varied in parallel through the range of motion, males always being stronger than females (Figure 43). No substantive sex-related design modifications were recommended on the basis of this pattern similarity. Any adjustable features on this machine were justified on the basis of anthropometry and not sex *per se*..

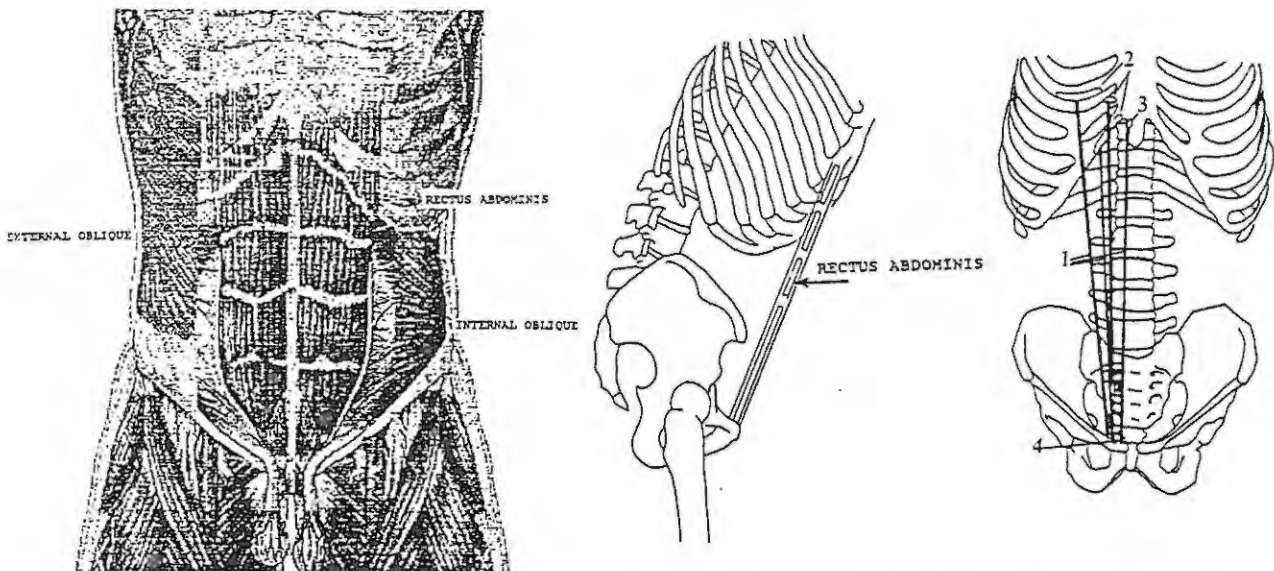
### 2.2. Relevant Muscles of the Mid-Section

The muscles involved in spinal flexion are in pairs, one on each side of the abdominal midline. They can function independently or together. The abdominal muscles do not attach directly to the vertebrae they move. When the abdominal muscles contract, the spine is pulled into flexion by the rib-cage moving towards the pelvis.

Three abdominal muscles are involved in spinal flexion. These are the rectus abdominis, and the internal and external obliques. Figure 44 shows the musculature involved in spinal flexion, the origin, course and insertion of these muscles, detailed descriptions of which can be found in Appendix IV.



**Figure 43:** Combined-sex and sex-based differences in isometric maxima produced at four test-points (15°, 45°, 70°, 90°) through the range of spinal flexion on the 'abdominal' unit.



WHERE: (1) Rectus Abdominis; (2) Cartilage of 5th-7th ribs; (3) Xiphoid process; (4) Crest of pubis.

**Figure 44:** Showing primary musculature involved in spinal flexion, their anatomical site (left) and origin, course, insertion (right), and direction of tension (centre).

### SECTION 3 : METABOLIC ANALYSIS

The metabolic cost of performing at fixed-rate submaximal efforts at steady state was determined by requiring a mixed-sex group to perform at two stress levels, 10% and 30% of each individuals one-repetition maximum (1 RM) while breathing through a portable oxygen analyzer. These are designated as 10% and 30% stress levels respectively.

It must be noted that the mean relative loads moved during the analysis are not the actual loads calculated for 30% and 10% 1 RM, as these calculated loads often did not correspond exactly to a load on the weight stack. Consequently, the load on the weight stack which most closely corresponded to the 10% and 30% 1 RM loads was used at each of these stress levels. Subjects analyzed were constrained to exercise continuously at a rate of 25 reps.min<sup>-1</sup> set by metronome, for 10 min at each of 10% and 30% stress levels. Table XIII summarises the metabolic findings of this study. Figure 45 illustrates the mean O<sub>2</sub> consumption for males and females at the two effort levels for the 10 min exercise period. As expected, mean metabolic cost at 0.1 and 0.3 stress levels for males and females on this machine is classified as "light" (McArdle et al., 1991).

It is difficult to quantitatively express the actual energy expenditure associated with the anaerobic component of the total energy expenditure. Psychophysical data (Section 4) may provide some indication as to the degree of anaerobic

energy supply. The psychophysical data show that at the 10% stress level there is very little difference between "local" (muscle) and "central" (cardiovascular) ratings of perceived exertion, for both males and females.

This low metabolic cost, in combination with the associated RPE, suggests that the intensity of the exercise was so low as not to tax the anaerobic system, and to impose only a very small aerobic cost. The same applies for females at the 30% stress level. However, under 30% stress, males tend to rate slightly higher than the females for both "local" and "central" factors. Further, the male RPE for "local" factors was slightly higher than the RPE for "central" factors. This tends to indicate that at the 30% stress level anaerobic pathways become more prominent.

Therefore, metabolic cost tends to be load dependent. At the 10% stress level, the light loads resulted in "light" metabolic costs associated with similar RPE's for both males and females. At the 30% stress level as load increases, "local" RPE becomes slightly higher than "central" RPE, without a concomitant increase in metabolic cost, indicating increased prominence of anaerobic pathways. Figure 45 indicates only a slightly higher metabolic cost at the 30% stress level for males.

Table XIV shows that at equivalent relative loads, energy expenditure for females was 0.75 of males at the 10% stress level and 0.58 that of males at the 30% stress level. It

therefore appears that absolute load and not relative load determine energy expenditure.

From these results it appears that at a 0.1 stress level aerobic pathways are prominent, but the associated energy cost is so low as not to have a major affect on weight loss. However, at a 0.3 stress level, the abdominal unit begins to emphasise anaerobic pathways. This indicates the machine being used to develop or enhance muscular strength and/or muscular endurance rather than as a weight-losing device.

Table XIV summarises the relative performance of the females in the sample. Figure 46 shows that female loads constitute 0.71 of male loads at max, 0.5 at 10% stress level and 0.6 at the 30% stress level. Females tend to be about 70% as strong as males, with a range of 59 - 84% depending on the muscle group tested (McArdle et al., 1991). It must be noted however, that some of the males at 1 RM were machine limited; that is some of the males could lift the entire weight stack but this was not necessarily their 1 RM. In contrast, the female subjects were in fact all exerting maximally below machine capacity.

**Table XIII:** Mean metabolic response to work on the abdominal machine at 10% and 30% 1 RM (Standard deviations in brackets).

	10% Stress Level		30% Stress Level	
	MALE	FEMALE	MALE	FEMALE
Relative Load (kg)	10	5	25	15
VO <sub>2</sub> (ℓ.min <sup>-1</sup> )	0.59 (0.01)	0.44 (0.05)	0.74 (0.03)	0.43 (0.02)
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )	8.06 (1.57)	7.44 (0.59)	9.88 (2.56)	7.68 (0.82)
METS	2.31 (0.45)	2.12 (0.17)	2.82 (0.73)	2.19 (0.23)
k cal.min <sup>-1</sup>	2.95 (0.04)	2.18 (0.23)	3.72 (0.13)	2.16 (0.10)
V <sub>e</sub> (ℓ.min <sup>-1</sup> )	19.58 (1.67)	12.88 (1.79)	23.25 (2.03)	14.2 (1.21)

NOTE: Mean male max (1 RM) was 81.9 kg (SD 7.18)  
 Mean female max (1 RM) was 58.1 kg (SD 6.25)

**TABLE XIV:** Female data, in percentage of male data (100.F/M) on the 'abdominal' machine.

	Stress Level	
	10% max	30% max
VO <sub>2</sub> (ℓ.min <sup>-1</sup> )	74.6	58.1
VO <sub>2</sub> (ml.kg <sup>-1</sup> .min <sup>-1</sup> )	92.3	77.7
METS	91.8	77.7
k cal.min <sup>-1</sup>	73.9	58.1
V <sub>e</sub> (ℓ.min <sup>-1</sup> )	65.8	61.1

NOTE:  
 Female 1 RM = 70.9% Male  
 Female 0.1 RM = 50% Male  
 Female 0.3 RM = 60% Male

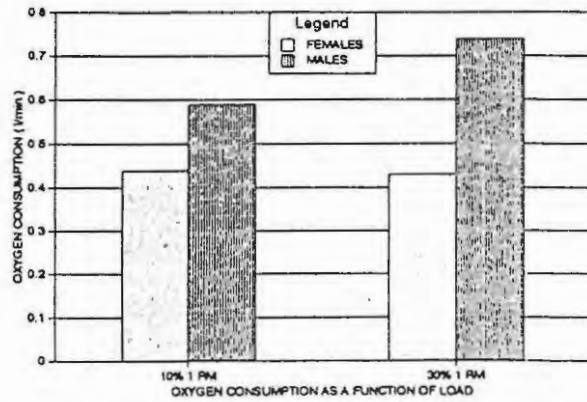


Figure 45: Mean oxygen consumption for males and females for the 10 min exercise period on the 'abdominal' unit.

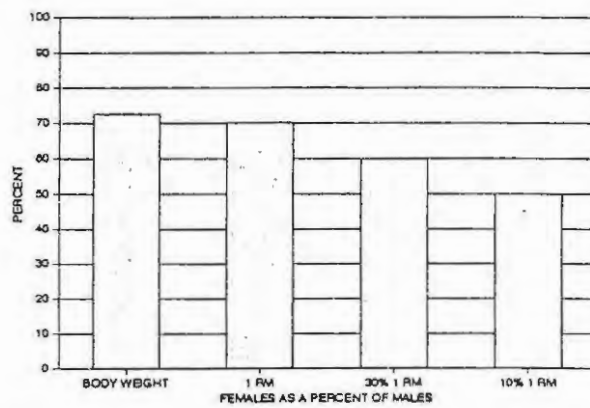


Figure 46: Differences based on sex: female body-weight and loads moved as a percentage of males on the 'abdominal' unit.

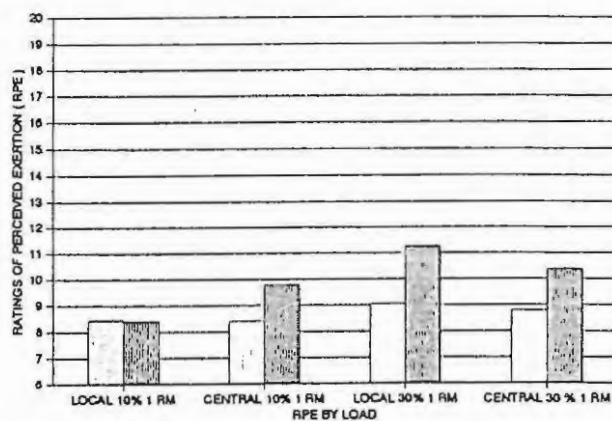


Figure 47: Ratings of perceived exertion at 10% and 30% stress levels on the 'abdominal' machine.

#### SECTION 4 : PSYCHOPHYSICAL ANALYSIS

Absolute loads at 10% and 30% stress levels were quite different for males and females. Table II shows females always moving lighter absolute loads than the males at the same relative load. However, the ratings of perceived exertion (RPE) were quite similar at each load despite these absolute load differences between the sexes.

At the 10% stress level males and females rated exertion in the abdominal musculature (local RPE) as "very light", while cardiovascular (central RPE) ratings ranged from "very light" to "fairly light". At the 30% stress level perceived ratings of abdominal exertion for females was "very light" and for males it was "fairly light". The same trend was noted for "central" ratings (Figure 47).

At the 10% stress level the low ratings of perceived exertion in the abdominal musculature and the low "central" ratings of perceived exertion reflect a low work intensity concomitant with in a low metabolic cost. At 30% 1 RM local and central ratings for females were very similar. In contrast, local RPE was slightly higher than the central RPE for males, suggesting a slightly higher work intensity than is indicated by  $O_2$  consumption ( $l \cdot \text{min}^{-1}$ ), or calculated energy expenditures ( $k \text{ cal} \cdot \text{min}^{-1}$ ) at the same relative loads (Table II).

## SUMMARY

In order to ensure optimal use of the length-tension relationship, a variable starting position mechanism was suggested for this unit. Further, the lever arm should be lengthened to reduce the degree of 'rolling' of the chest pad on the chest. Eccentric cams were redesigned according to isometric maxima generated at four points in the range of motion.

The metabolic analysis indicated that metabolic cost of working on the abdominal unit for 10 minutes at 0.1 and 0.3 stress levels was classified as light. Psychophysical data showed that the ratings of perceived exertion (RPE) were similar at each relative load, despite absolute load differences between the sexes. At the 30% stress level females rated local and central RPE similarly. In contrast, males rated local RPE slightly higher than central RPE.

Therefore, in conclusion, at 0.1 stress level the abdominal unit did not tax the anaerobic system, and imposed a very small aerobic cost, for males and females. This was the trend for females at the 0.3 stress level. For males at the 30% stress level, anaerobic cost became more prominent. Therefore metabolic cost on this machine tends to be load dependent. This unit is not effective as a weight loss device as the aerobic energy pathway is not sufficiently taxed even at the lightest load for 10 minutes.

## **ANALYSIS FIVE : HIP-ABDUCTION UNIT**

### **INTRODUCTION**

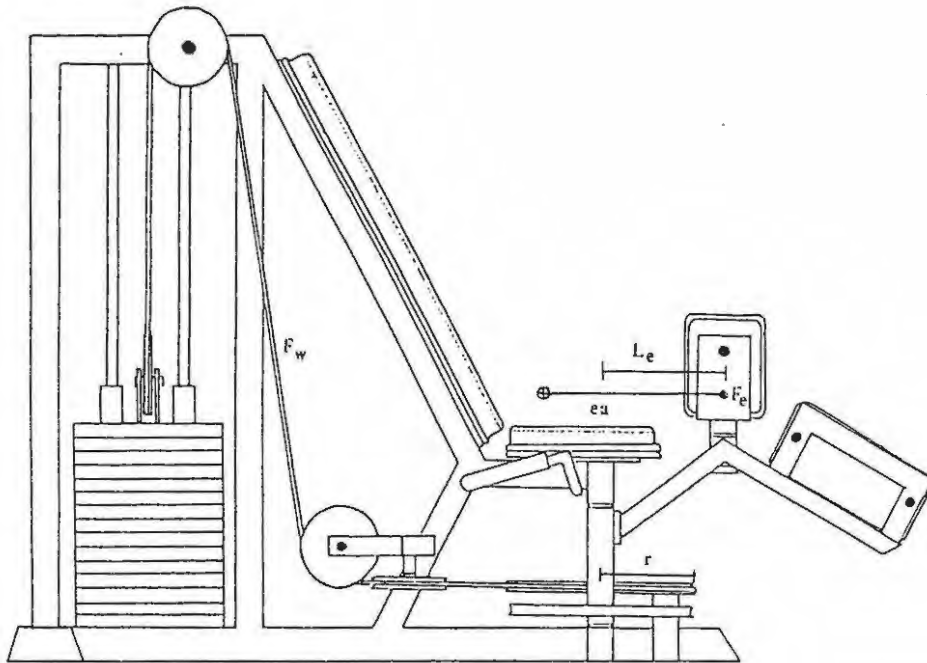
The seated hip-abductor machine permits seated unilateral and/or bilateral hip abduction through a range of approximately 50°. The design is such as to standardize operator position comfortably by providing a back rest and leg rests.

Load adjustments commensurate with operator capacity can easily be reset, and the range and step-increments of the weights, and the swivelling upper-thigh supports indicate a design intended to accommodate users of diverse levels of strength and body size.

It was decided not to conduct a metabolic analysis on this unit, for two reasons. Firstly, an extremely small musculature is utilised for this exercise, and secondly, it had been established from the previous analyses that isoinertial accommodating resistance exercise does not sufficiently tax the aerobic component of energy metabolism to warrant its study.

### **SECTION 1 : ENGINEERING ANALYSIS**

Musculo-skeletal leverage through a normal range of motion is such that muscle force available for movement varies depending upon lever configuration, muscle length and other factors.



- NOTE :
- $F_w$  is the myometer reading in newtons
  - $F_e$  is the force exerted against the machine in newtons
  - $L_e$  is the lever arm from the centre of the thigh pad to the machines' centre of rotation
  - $ea$  is the effort arm from the centre of the hip joint to the centre of the thigh pad
  - $r$  is the cam radius from the centre of cam rotation to the centre of the cable

**FIGURE 48:** Showing levers used in the derivation of equations required to calculate muscle torque on the hip-abduction unit.

Ergonomic redesign of isoinertial accommodating resistance equipment attempts to match the mechanical requirements of the machine with the biomechanical characteristics of the human musculo-skeletal system. This essentially requires devising an accommodating resistance system which would ensure that the torque required by the machine changes at the same rate and in the same direction (increase or decrease) as the torque exerted by the user through the range of motion. Figure 48 depicts the relevant levers used to ensure that the resistive moments are exactly counterbalanced by the effort moments so that equilibrium is attained such that:

$$F_w \cdot r = F_e \cdot L_e \dots \dots \dots \text{So: } F_e = F_w \cdot \frac{r}{L_e} \quad (1)$$

Given that the force ( $F_e$ ) has the moment arm  $ea$ , a perpendicular distance from the line of force to the axis, then the equation of moment equilibrium for muscle torque in the hip abduction machine is:

$$T_m = F_e \cdot ea \quad (2)$$

However: (1) and (2) have different fulcra of balance

From (1):  $F_e = F_w \cdot \frac{r}{L_e}$

Therefore:  $T_m = F_w \cdot \frac{r}{L_e} \cdot ea$

So:  $T_m = F_w \cdot r \cdot \frac{ea}{L_e}$

Figure 49 shows the pattern of musculo-skeletal torque generated isometrically by a mixed-sex group of active young adults at 4 position of hip-abduction ( $15^\circ$ ,  $25^\circ$ ,  $35^\circ$ ,  $50^\circ$ ). The cam radius must increase or decrease in tandem with increases or decreases of force exerted by the user ( $F_u$ ), in this way ensuring that the torque required by the machine increases or decreases at the same rate of increase or decrease as the torque exerted by the user through the range of motion. Redesigned cam radii are presented in Table XV, while Figure 50 illustrates the discrepancy between the present cam radii and the radii of the redesigned cam with Figure 51 depicting the shape of the redesigned cam.

The primary suggested design alteration on the hip abduction unit is that the seat be inclined by  $10^\circ$  (Figure 52). This can be cost-effectively implemented by an additional wedge under the seat support. This suggestion was the result of complaints by numerous users who stated that: gripping the hand grips for support, while executing the exercise, caused them to slide forward on the seat. Therefore, it was felt that by inclining the seat, users would pull their buttocks into the seat, providing a more "hugging" seating configuration. Figure 52 shows that the inclined seat will not require any alterations to the swivelling upper-thigh supports. In its present design configuration the upper-thigh supports are higher than the seat. This means that only the buttocks and not the remainder of the upper thighs are in support.

Consequently, inclining the seat will mean that more of the upper leg is supported by the apparatus during the exercise.

The present leg support design ensures that the knee is flexed and therefore, that the lateral musculature of the thigh is neutralised, ensuring that only the musculature described in Section 2 is employed. However, in lateral movements involving hip-abduction, the legs may be in a fully extended position. Extended-knee hip-abduction may also be beneficial in remediating injuries to the lateral ligaments of the knee, for example, where utilisation of the lateral thigh musculature may be beneficial. Therefore, it was felt that if this could be implemented cost-effectively, an apparatus allowing users the option of performing the exercises with either flexed or fully extended knees, would increase the marketability of the unit.

It has been noted that hip-abduction should be performed with the upper body and upper legs in a straight line. The argument put forward for this is that when there is flexion at the hips because of a raised back-rest (i.e. seated position), the gluteus medius no longer acts in a straight line from its origin to insertion. Thus, multiple repetitions could irritate the joint, which in time could also cause injury. Also, when the body is in a relatively straight position, it duplicates more closely the actions used in normal everyday activities like running, jumping, lateral movements and walking.

**TABLE XV:** Mean isometric hip-abduction force, derived torque and associated positional and machine specification factors, for a combined-sex group of active young adults.

PARAMETER	DATA				DERIVATION
DEGREES OF FLEXION	15° START	25°	35°	50° FINISH	(MEASURED)
Cam Radius (m)	0.148	0.145	0.142	0.142	(measured)
Myometer ( $F_w$ ) (Nm)	960.5	951.9	832	653.6	(recorded)
Torque ( $T_m$ ) (Nm)	198.8	176.3	144.8	113.5	$(F_w \cdot r \cdot ea / L_e)$
Force exerted against machine ( $F_e$ ) (N)	612.7	594.9	509.2	400.0	$(F_w \cdot r / L_e)$
Adjusted Cam Radius (m)	0.17	0.15	0.123	0.097	(based on 0.17m set at 15°)
Adjusted $F_w$ (N)	1169.4	1175.3	1177.2	1170	$(T_m + \text{adj cam})$

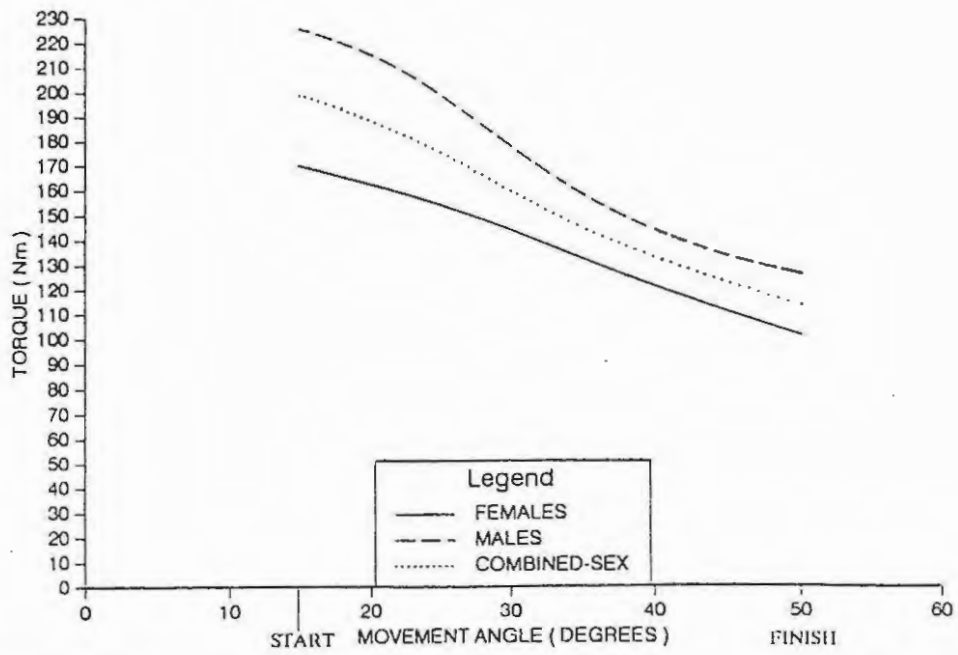


FIGURE 49: Pattern of musculo-skeletal torque as a function of four positions in the range of motion on the hip-abduction unit.

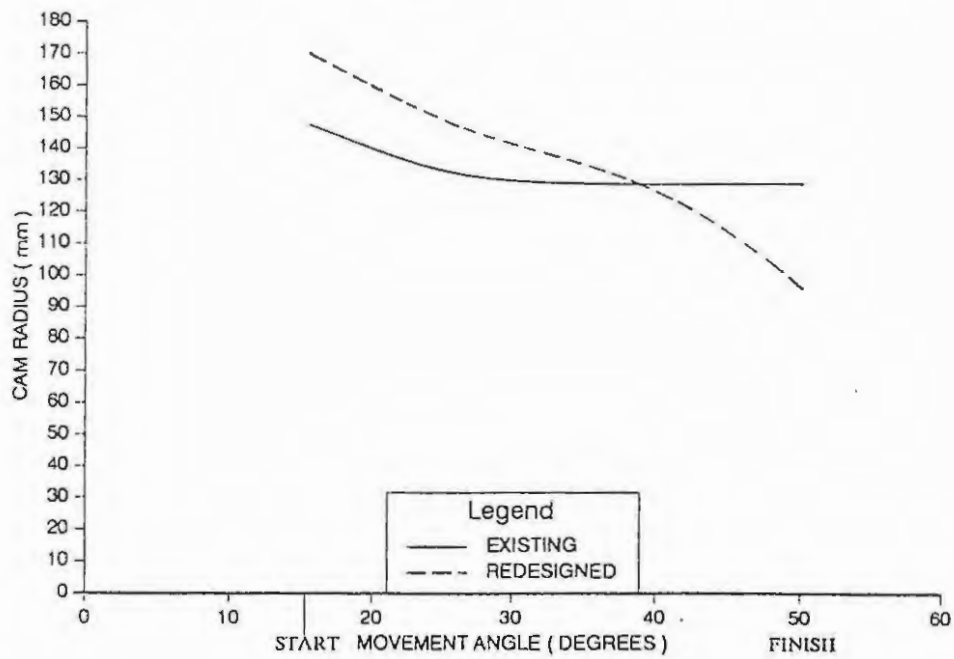


FIGURE 50: Showing radii of presently installed and redesigned cams on the hip-abduction unit.

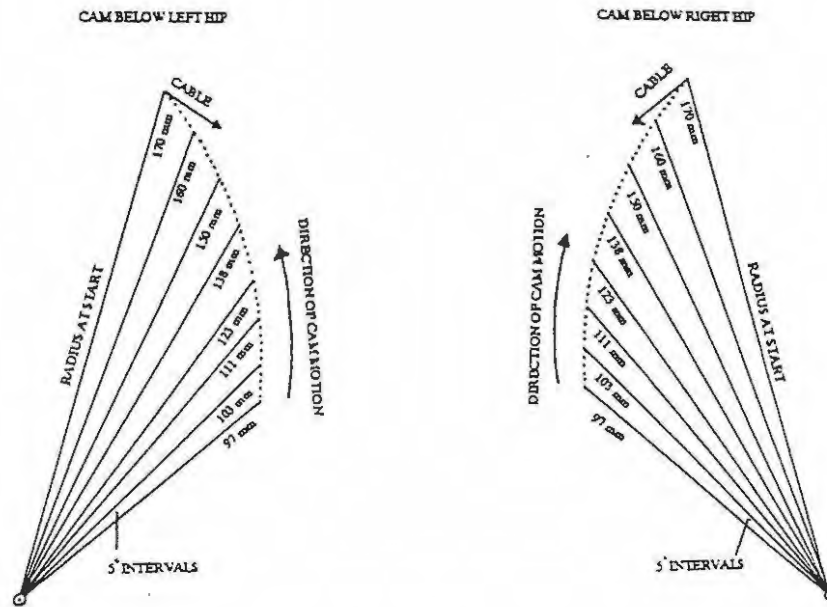


FIGURE 51: Redesigned cam shape on the hip-abduction unit based on radii provided in Figure 50 and Table XV.

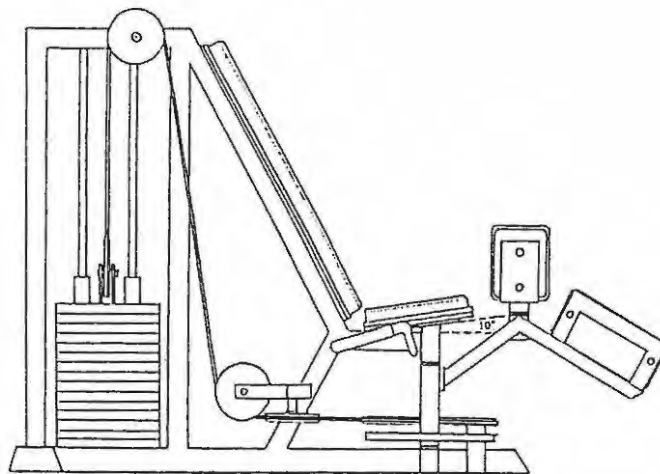


FIGURE 52: Revised incline seat position on the hip-abduction unit.

## SECTION 2 : MUSCULO-SKELETAL ANALYSIS

### 2.1 Isometric Torque Maxima

Table XV summarises the combined-sex maximal isometric force and torque data of a group of healthy, active young adults of both sexes, who participated in this study. Isometric maxima were tested at four selected positions through the range of motion. Figure 53 shows that the males were consistently significantly stronger than the females through the range. The first 10° of movement (hip abduction) shows that females reach peak force at approximately 25° of hip abduction whereas males peak force is at the beginning of the movement. Males and females responded similarly for the remainder of the range.

Any adjustable features of the machine are justified on the basis of body-size, not sex *per se*, since the pattern in similarity between the sexes (except the initial minor difference) confirmed that no substantive sex-related design modifications were needed.

### 2.2 Relevant Muscles of the Hip

Figure 54 shows the primary musculature utilised in hip abduction. The anterior fibres of the medius act as a medial rotator and flexor, and the posterior part as a lateral rotator and extensor of the hip, while the entire muscle functions as an abductor. Figure 54 shows the origin, insertion and course of these muscles with detailed explanations appearing in

## Appendix V.

The gluteus medius and leg abduction are used in all activities requiring side stepping or lateral movement. Such as soccer, field hockey, and racquet sports. Leg abduction is also the key action in shifting your body weight in the hitting and throwing sports. This occurs when you push off your rear leg to get your body weight onto your forward leg.

Both the gluteus medius and minimus play an essential part in maintaining the trunk upright when the foot of the opposite side is raised from the ground in walking and running, the body weight tending to make the pelvis sag downwards on the unsupported side. This tendency is counteracted by the glutei of the supporting side, which, acting from below, exert such powerful traction on the hip bone that the pelvis is actually raised a little on the unsupported side. These muscles are inactive in symmetrical standing. Paralysis of the gluteus medius and minimus is the most serious muscular disability in the region of the hip. When these two muscles remain intact, even though many others acting on the hip joint are paralysed, the patient is able to walk, or even run, with remarkably little instability. The tensor fascia assists the anterior bundles of the gluteus medius and minimus in postural abduction at the hip joint.

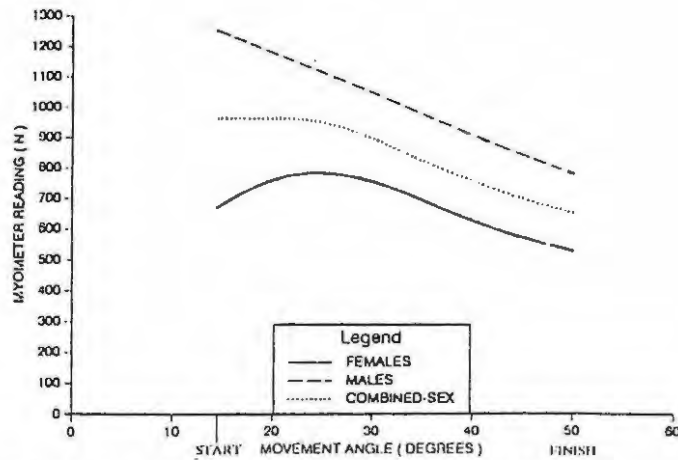
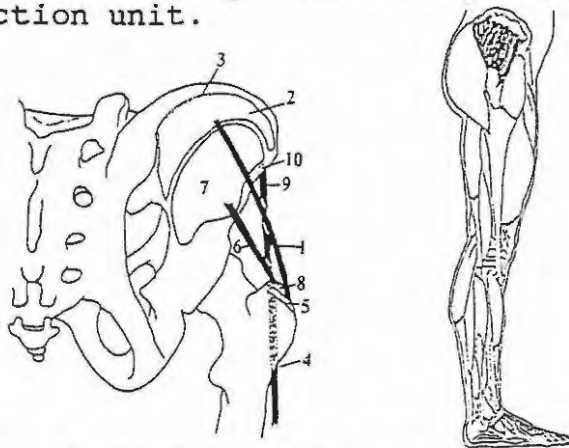


FIGURE 53: Sex-based and combined-sex differences in isometric maxima at four test points through the range of motion on the hip-abduction unit.



WHERE: (1) Gluteus medius; (2) Gluteal surface of the ala of the ilium; (3) Iliac crest; (4) Iliotibial tract; (5) Greater trochanter; (6) Gluteus minimis; (7) Greater area on the ala of the ilium; (8) Greater trochanter; (9) Tensor fascia latae; (10) Anterior superior iliac spine.

FIGURE 54: Origin, course and insertion (left) and anatomical site (right) of primary musculature involved in hip abduction.

#### SUMMARY

Musculo-skeletal torque generated by a mixed-sex group showed that the eccentric cam was incorrectly shaped, redesign was initiated accordingly. The only other design alteration recommended on this unit was that an inclined seat ( $10^{\circ}$ ) be implemented to ensure a more 'hugging' seating arrangement.

## **ANALYSIS SIX: 'UNDER-OVER' PULLEY UNIT**

### **INTRODUCTION**

The "high-low" double swivel pulley-unit allows for a large spectrum of exercises, to be carried out by two people simultaneously, on either the upper or lower body.

A wooden cross-bar at each end of the apparatus allows for necessary operator support while performing certain exercises on the legs and upper body. The 180° swivelling pulleys mean that user position is always optimal while exercises are being performed.

In the absence of eccentric cams on this apparatus, it was unnecessary to determine isometric torque maxima. Due to the wide choice of possible exercises on the apparatus, metabolic cost and psychophysical analysis were not relevant. Further, musculo-skeletal analysis was not conducted. Instead the versatility of the unit has been demonstrated via analysis of the force demands caused by varying body position in terms of user distance from the pulley apparatus. This has involved analyzing movements performed at distances of 0.5m ( designated "near") and 1.0m ( designated "far") from the pulley unit.

### **MEASUREMENT METHODOLOGY**

In order to calculate the movement and joint components while performing elbow flexion and extension movements on the pulley apparatus, it was necessary to determine the acute angle ( $\theta$ ) between the line of the cable and the long axis of

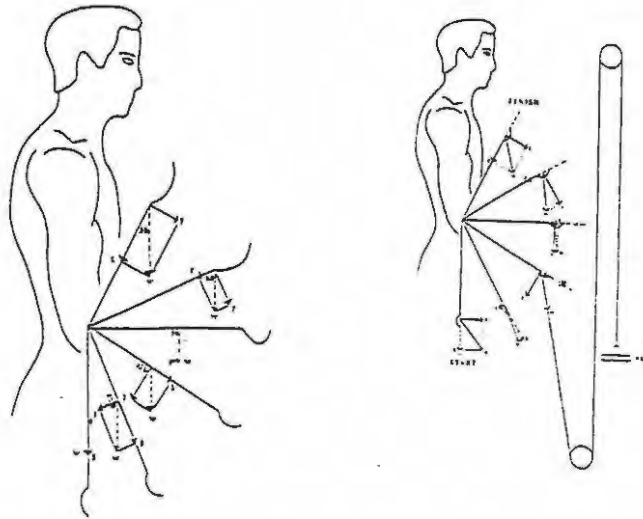
the forearm (See Figure 55 and 56).

Consequently, the subject was required to stand at distances of 0.5m and 1.0m away from the apparatus for both elbow flexion (low pulley) and elbow extension (high pulley). At each of these distances, and for each exercise, the acute angle ( $\theta$ ) was measured, at 30° intervals, during the full range of motion, i.e. 30°, 60°, 90°, 120°, 150°, 0° flexion. In each instance the upper arm was held in a fixed pendant position and the elbow angle was determined using a flexometer. The midpoint of the elbow was marked, as were the axes of the forearm and upper arm, in order to ensure consistency of measurement. In each position of elbow flexion, the acute angle between the cable and forearm axis was then measured using the flexometer. These measured angles are shown in Tables XVII, XIX, XXII and XXIV.

#### **BIOMECHANICAL CONSIDERATIONS AND CALCULATIONS**

In order to demonstrate the effect of standing nearer or further from the apparatus, it was decided to analyze a simple elbow flexion exercise on the lower pulley and a simple elbow extension exercise from the upper pulley.

The mass of the subjects upper extremity, distal to the elbow joint, was calculated once the subject's body mass had been determined. The concept behind this is that as you flex or extend the forearm-and-hand alone, their weight, acting vertically



c = component of the force tending to compress the elbow joint.  
 s = component of force tending to separate the elbow joint.  
 r = component of force tending to rotate the forearm.  
 w = resultant force due to the pulley system.

**FIGURE 55:** Showing the vectors of the forearm-and-hand alone (left) and during elbow flexion on the low pulley while standing near (0.5m).

downward throughout the range, may be resolved into two component forces, at right angles to each other and one of them always at right angles to the longitudinal axis of the forearm (Figure 55). This perpendicular component of the total force is the component tending to rotate the forearm-and-hand about the elbow joint. This "turning" component must be overcome if flexion is to occur, and provides, therefore, the "exercise force". The component at right angles to this "exercise force" lies along the axis of the forearm and its direction indicates its tendency to compress the forearm into the upper arm at the elbow joint, or to separate the elbow joint. Tables XVI and XXI show the calculated rotating and compressive/separating forces for this subject.

Normally, in flexion/extension of the forearm-and-hand about the elbow joint, the load acts vertically. However, when the exercises are performed on the pulley unit, the apparatus load has the direction of the cable. The component tending to rotate the limb above the elbow must act perpendicularly to the forearm. A second component, at right angles to the rotating component, lies along the axis of the limb and its direction shows the tendency to compress or separate the forearm at the elbow joint. Figures 55 and 56 show these vector forces for elbow flexion and extension respectively.

Calculations of the compressive/separating and rotatory components of both the forearm-and-hand and the pulley system are made using simple trigonometry. Referring to Figures 55, and 56, if the acute angle between the line of the cable and the long axis of the arm is known ( $\theta$ ) then:

$$\sin \theta = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{\text{rotatory component}}{W}$$

$$\sin \theta = \frac{\text{Rotatory}}{W}$$

$$\therefore \text{Rotatory component} = W \cdot \sin \theta$$

and

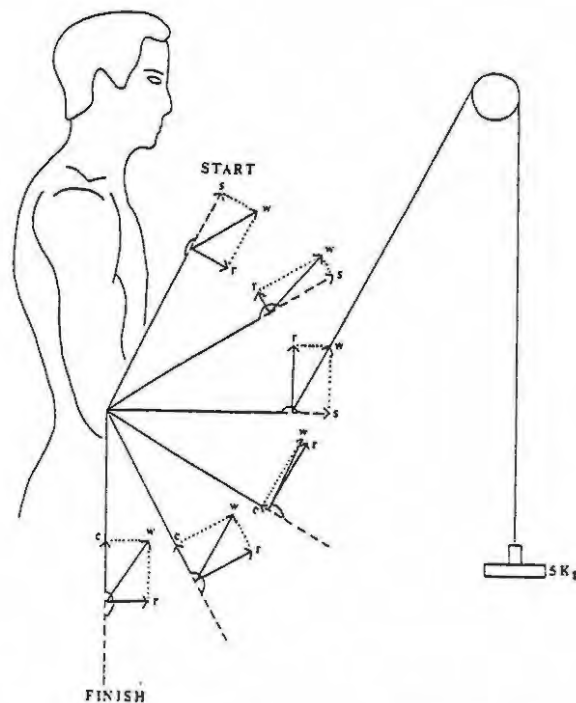
$$\cos \theta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{\text{compressive/separating component}}{\text{weight}}$$

$$\cos \theta = \frac{\text{compressive/separative}}{\text{weight}}$$

$$\therefore \text{Compressive/separative component} = W \cdot \cos \theta$$

It must be noted that the vectors applicable to the load of the hand-and-forearm alone, and those of the cable all

originate from the same point of origin since only force, and not torque, is being considered. Although the resultants have different directions, their components, being either perpendicular to (rotatory) or along the longitudinal axis (compressive/separating) of the forearm, have the same direction. Thus the total "exercise" force is the sum of components due to the weight of the limb and the load along the pulley cable. Tables XVII through XX show results for the pulley system alone and combined with the forearm mass when near the apparatus (0.5m) and far (1.0m) from the apparatus for elbow flexion, and the results for elbow extension are shown in Tables XXII through XXV. Graphic representation of these results is shown in Figures 57 and 58.



**FIGURE 56:** Showing relevant vectors during elbow extension on the high pulley while standing near (0.5m)

TABLE XVI: Force components of forearm-and-hand alone (1.57 kg)

	Degrees of Flexion	Rotating Component (kg)	Compressive (+) or Compressing (-) Component (kg)
Start	0° (Full extension)	0	1.57 (-)
	150°	0.79	1.36 (-)
	120°	1.36	0.79 (-)
	90°	1.57	0
	60°	1.36	0.79 (+)
Finish	30° (Full flexion)	0.79	1.36 (+)

TABLE XVII: Force components of the pulley system alone for elbow flexion - standing near (0.5m) against 5kg resistance.

Degrees of Flexion	θ	Rotating Component (kg)	Separating (-) or Compressing (+) Component
0° (Full Extension)	39°	3.25	3.69 (-)
150°	6°	0.52	4.57 (-)
120°	49°	3.77	3.26 (-)
90°	81°	4.54	0.78 (-)
60°	65°	4.53	2.11 (+)
30° (Full flexion)	40°	3.21	3.63 (+)

TABLE XVIII: Force components of the limb and pulley combined for elbow flexion - standing near (0.5m).

Degrees of Flexion	Rotating Component (kg)	Separating (-) or Compressing (+) Component
0° (Full extension)	3.25	5.46 (-)
150°	1.31	6.53 (-)
120°	5.13	4.07 (-)
90°	6.51	0.76 (-)
60°	5.89	2.9 (+)
30° (Full flexion)	4.00	5.19 (+)

TABLE XIX: Force components of the pulley system alone for elbow flexion - standing far (1.0m) with a resistance of 5 kg.

Degrees of Flexion	θ	Rotating Component (kg)	Separating (-) or Compressing (+) Component
0° (Full extension)	44°	3.47	3.60 (-)
150°	19°	1.63	4.73 (-)
120°	23°	1.95	4.60 (-)
90°	60°	4.23	2.5 (-)
60°	81°	4.94	0.78 (+)
30°	48°	3.72	3.35 (+)

TABLE XX: Force components of the limb and pulley combined for elbow flexion - standing far (1.0m).

	Degree of Flexion	Rotating Component (kg)	Separating (-) or Compressing (+) Component
Start	0° (Full extension)	3.47	5.17 (-)
	150°	2.42	6.09 (-)
	120°	3.31	5.39 (-)
	90°	5.9	2.5 (-)
	60°	6.3	1.57 (+)
Finish	30° (Full flexion)	4.51	4.71 (+)

TABLE XII: Force components of forearm-and-hand load alone for elbow extension (1.57 kg)

	Degree of Flexion	Rotating Component (kg)	Compressing (+) or Separating (-) Component (kg)
Start	0° (Full extension)	0	1.57 (-)
	150°	0.79	1.36 (-)
	120°	1.36	0.79 (-)
	90°	1.57	0
	60°	1.36	0.79 (+)
Finish	30° (Full flexion)	0.79	1.36 (+)

TABLE XIII: Force components of the pulley system alone for elbow extension - standing near (0.5m) with a resistance of 5 kg.

Degree of Flexion	α	Rotating Component (kg)	Separating (-) or Compressing (+) Component
0° (Full extension)	36°	2.94	4.05 (+)
150°	58°	4.24	2.65 (+)
120°	87°	4.99	0.26 (+)
90°	62°	4.41	2.35 (-)
60°	17°	1.46	4.78 (-)
30°	33°	2.72	4.19 (-)

TABLE XIII: Force components of the limb and pulley combined for elbow extension - standing near (0.5m).

	Degree of Flexion	Rotating Component (kg)	Separating (-) or Compressing (+) Component
Finish	0° (Full extension)	2.94	2.48 (-)
	150°	5.03	1.29 (-)
	120°	6.25	0.53 (-)
	90°	5.68	2.35 (-)
	60°	2.62	3.59 (-)
Start	30° (Full flexion)	3.51	2.63 (-)

TABLE XIV: Force components of the pulley system alone for elbow extension - standing far (1.0m) with a resistance of 5 kg.

Degree of Flexion	α	Rotating Component (kg)	Separating (-) or Compressing (+) Component
0° (Full extension)	52°	3.94	3.08 (+)
150°	77°	4.67	1.12 (+)
120°	76°	4.85	1.21 (+)
90°	43°	3.41	3.66 (-)
60°	3°	0.26	4.99 (-)
30° (Full Flexion)	51°	3.89	3.15 (-)

TABLE XIV: Force components of the limb and pulley combined for elbow extension - standing far (1.0m).

	Degree of Flexion	Rotating Component (kg)	Separating (-) or Compressing (+) Component
Finish	0° (Full extension)	3.94	1.51 (+)
	150°	5.66	1.24 (+)
	120°	6.21	0.42 (+)
	90°	4.98	3.66 (-)
	60°	1.62	4.2 (-)
Start	30° (Full flexion)	4.68	1.79 (-)

## APPLICATIONS OF BIOMECHANICAL PRINCIPLES

### Elbow Flexion : Low Pulley

In comparing the two conditions (near and far), Figure 57 shows that a greater rotating force (kg) is generated up until 130° of flexion when standing further away from the apparatus (1.0m). From full extension until 150° flexion the rotating force initially decreases for both conditions, whereafter it begins to increase. From 150° to 120° of flexion there is an increase in the rotatory component for both near and far conditions, with standing near generating a more "accelerated" rotatory component. From 130° of flexion, a greater "exercise" force is generated by standing nearer the apparatus. This is continued until approximately 75° of flexion. The greatest rotating force is generated at 90° of flexion when standing near, in contrast to standing further away, where the peak force is at 60° of flexion. The rotating forces decrease until "full flexion" at 30° of flexion for the two conditions. From 70° flexion until full flexion, standing further away from the pulley generated the greater rotating force.

The different shadings utilised in Figure 57 show that standing nearer the apparatus generates a greater rotating component during the mid-range of the movement, while the opposite is true for the outer limits of the range of motion. Thus, the variation in user position from the pulley-unit provides a number of implications for its use.

Firstly, an individual who performs the elbow flexion exercise on a regular basis may experience difficulty on some occasions and apparent ease on others in performing at an anticipated level due to the fact of standing at differing distances from the machine during each training session.

An elite athlete requiring specific training over a certain portion of the range could alter position accordingly. Thus, an athlete requiring greater strength in the mid-range of total elbow flexion could stand nearer the apparatus since a greater force is generated during this portion (Figure 57). The same applies to the outer ranges of elbow flexion where it would be more beneficial to stand further away from the apparatus.

A further consideration must be adopted when elbow flexion is executed in a clinical environment. For example, an individual requiring strengthening of the arm following surgery, complains of weakness in the elbow joint, associated with dull but not remarkable pain following training. The pain implies a need to provide stability in the joint during the exercise, therefore a compressive component rather than a separating component would be preferable. "Weakness" indicates a need to increase strength, while consequently limiting the experienced pain. This dilemma could be solved by studying Figure 5 which shows the movement and joint components exists up until 90° flexion for both near and far conditions.

However, the magnitude of the rotating component is less, until 90° flexion, when standing further away. Therefore, two options are available: the exercise is only executed from 90° of flexion, with maximum force generated during this range when standing further away from the apparatus, or if the individual can perform through the full range then the exercise should be completed standing further away from the apparatus.

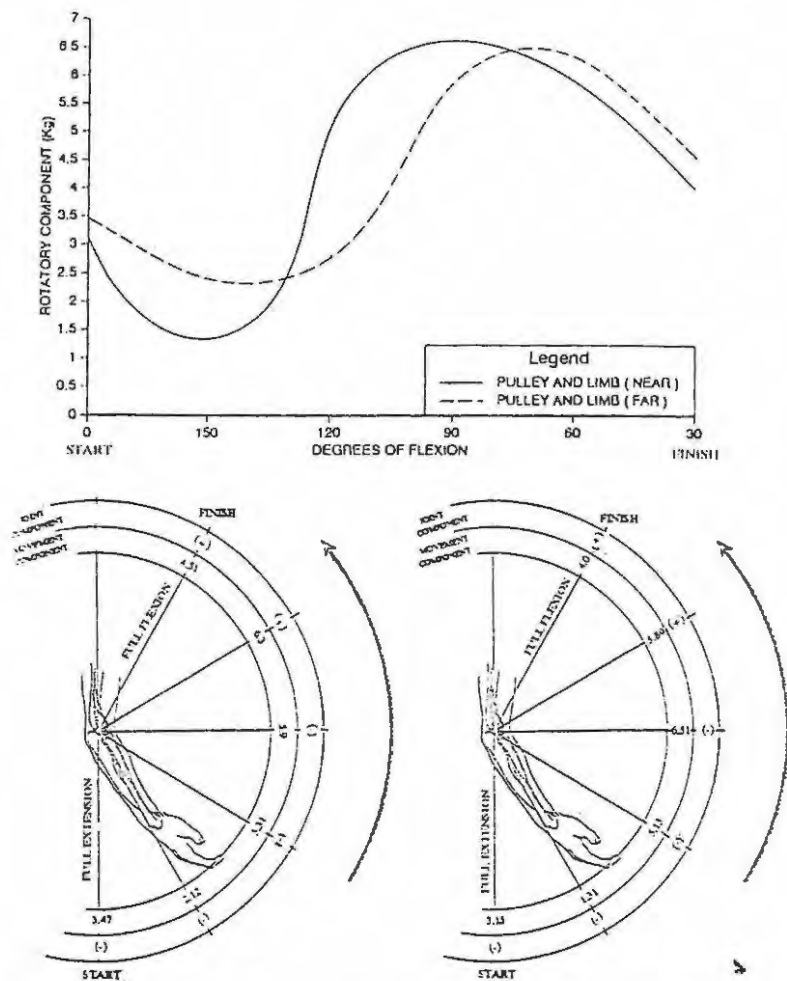


FIGURE 57: Rotatory components of elbow flexion on the low pulley (top), and combined joint and movement components during elbow flexion when standing near to (bottom left) and far from (bottom right) the pulley-apparatus.

### **Elbow Extension : High Pulley**

During the first 30° of movement, the rotating force decreases for both conditions. However, standing further away generates a slightly greater "exercise" component than standing nearer the apparatus initially. From then on standing nearer always generates a greater rotatory component until 130° of flexion, whereafter the reverse trend occurs until the movement is complete. Peak force is generated at 110° flexion when standing near the apparatus, and at 125° flexion when standing further away from the apparatus (Figure 58).

The different shadings used in Figure 58 indicate a greater rotating force is produced during the initial 80° of flexion, by standing nearer the apparatus. In comparison, a greater "exercise" force is generated during the terminal 60° of extension when standing further away from the apparatus.

The same implications described for elbow flexion can be applied for elbow extension, with the inclusion of a further possibility. When an individual is required to strengthen the arm through the full range of motion, in a clinical setting, in order to maximise the amount of rotating force possible, the following could be utilised. Ask the individual to initially begin the exercise standing near the apparatus and execute the movement until 130° of flexion whereupon the individual is to take a step backwards (to 1.0m). This means that (from Figure 58) greater force is generated when standing near until



## ENGINEERING ANALYSIS

While no formal measurements have been conducted, the following "weaknesses" have been observed while the apparatus has been in use.

1. While the wooden bars at each end of the apparatus offer user support they sometimes hinder movements, especially on the lower pulley as the cable rubs against it. This results in the pulley-apparatus dictating user position or distance from the apparatus. It is suggested that the distance of the supporting bars from the apparatus be reduced, and that extended handles be implemented from either end of the support bars.
2. It was noted that extremely tall individuals (1.95m) using the apparatus, are not able to work through a full range, especially during elbow extension on the upper pulley. The range was not limited by the weight stack striking the upper pulley, but rather by the fact that elbow extension could only begin at approximately 60° of flexion rather than at full flexion (app. 30° flexion). This is even the case when the individual is kneeling on the floor. It is therefore a possibility that the apparatus should be increased in height to accommodate extremely tall users.

## CHAPTER FIVE

### SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

#### STATEMENT OF THE PROBLEM

This study evaluated six items of South African-manufactured exercise equipment designed to effect optimal strength gains. Whether the design allows a piece of equipment to be used as originally intended by the designer is problematic, and contrived advertising claims by manufacturers of this equipment have gone largely unchallenged. Therefore, the problem at issue is whether equipment design is compatible with the musculo-skeletal and perceptual needs and limitations of the human user.

#### METHOD

In order to determine whether or not the needs and limitations of the user were congruent with equipment design, the format of the research undertaken in this study was in the tradition of ergonomics, which is typically in the nature of survey, problem identification, re-design, and trial and error elimination; that is, which utilises but does not rely solely upon empirical research study.

Given that ergonomics is inter-disciplinary in nature, knowledge from diverse fields such as physiology, psychology and biomechanics was drawn upon, the fundamental goal being to formulate generalised statements and recommendations with

respect to musculo-skeletal exertions on this type of equipment, with implications for injury rehabilitation and prevention, sports training and occupational safety.

## RESULTS

1. Analysis of the eccentric cams on all five pieces of variable resistance machinery indicated that all cams were incorrectly shaped. They were redesigned accordingly.
2. The initial starting position on the 'pec-fly' machine was found to be extreme and was altered by introduction of an adjustable wedge. The hand-grips were repositioned to reduce potentially harmful wrist flexion.
3. A device permitting variable back-rest angle on the knee extension unit was implemented so as to permit stressing of either all the knee extensors or only the one-joint vasti. Hand-grip angle was also altered to increase user comfort.
4. On the 'pullover' unit, the machine's fulcrum was placed anterior to the back-rest, in line with the user's fulcrum, thereby decreasing the utilisation of the elbow and wrist musculature. The seat's support bar was raised to increase the range of motion, while the machine's lever arm was extended to more greatly stress the musculature used in vertical shoulder extension.
5. A pegging mechanism allowing variable starting positions was suggested on the abdominal unit, in order to accommodate a diversity of chest depths. The machine's lever arm was

extended thereby reducing the 'rolling' of the chest pad.

6. The seat of the hip abduction unit was inclined by  $10^\circ$  to stop the user from sliding forward on the seat as the exercise is executed.

7. Analysis of the variable resistance machinery showed that for isometric torque maxima, males and females responded similarly, their isometric maxima varying in parallel through the range of motion, with males being, as expected, consistently significantly stronger than the females.

8. In all cases, absolute loads moved during metabolic analyses were quite different for males and females at the stress levels imposed, with males always moving heavier loads at each relative load and it was determined that absolute and not relative loads determined energy expenditure.

9. Metabolic cost on the four units analysed was clarified as 'light' with oxygen consumption ranging from  $0.28 \text{ l}\cdot\text{min}^{-1}$  to  $0.93 \text{ l}\cdot\text{min}^{-1}$ , and calculated energy expenditure ranging from  $1.27$  to  $4.20 \text{ kcal}\cdot\text{min}^{-1}$ .

10. Despite the absolute load differences, the ratings of perceived exertion (RPEs) were quite similar at each relative load. RPEs at both 30% and 50% max reflected a higher intensity of work than was indicated by either measured  $\text{O}_2$  consumption ( $\text{l}\cdot\text{min}^{-1}$ ) or derived energy expenditure ( $\text{kcal}\cdot\text{min}^{-1}$ ) for the 'pec-fly' and knee extension units.

11. The 'pullover' and 'abdominal' analyses showed that there was little difference between the 'local' and 'central' RPEs

for both males and females at the 10% stress level. At the 30% stress level males rated slightly higher than females for both 'local' and 'central' factors and male 'local' RPE was slightly higher than 'central' RPE. Perceptual responses indicated that only at 30% stress levels do the local cues begin to dominate, suggesting an increased predominance of anaerobic pathways.

## CONCLUSIONS

Variable resistance machines were originally conceived in an attempt to vary the resistance experienced by the working muscle through its range of motion, i.e. to maintain constant tension in the muscle, in order to mirror its associated strength curve (Fleck and Schutt, 1985; DiNubile, 1991). The present engineering analysis of a range of variable resistance isotonic equipment has showed that a number of design alterations could cost-effectively improve the use, comfort, safety and function of the machinery. A common thread appearing throughout the engineering analysis on all five pieces of machinery was the discovery that the eccentric cams were incorrectly shaped.

The isometric torque maxima generated on each piece of equipment provided a means of determining the required radii and therefore the cam shape needed to duplicate the torque curve. Once it was concluded that the existing cams were incorrectly shaped, it was then necessary to determine a means of altering the shape. It was not known on what grounding the

existing cams had been designed and it was initially thought that perhaps they had been placed upside down on the machines, or that the radii changed in the correct ratio, but not relative to appropriate positions through the range of motion.

Upon further investigation it was concluded that there was no easy way to reposition the cams and consequently they were completely redesigned, on the basis of the isometric torque curves derived experimentally.

There appeared to be more or less equal demands made of the aerobic and anaerobic energy-supply systems, although the extent to which the latter contributes to the total energy demand can only be inferred from the psychophysical data. Perceptual responses indicate that the work done is "light" and only at the 30% stress levels do local cues begin to dominate. It was concluded though, that in general the higher the absolute load, and/or the smaller the muscle group(s) taxed, the greater the anaerobic contribution to the total energy demand.

From the psychophysical work conducted it appeared that irrespective of the muscle groups tested, the metabolic and psychophysical responses to submaximal (10%, 30% and 50% stress levels) fixed rate isoinertial lifts were similar. Analysis of the 'pec-fly' and knee extension units showed that absolute loads were quite different for males and females at 30% and 50% 1RM, with males always moving heavier loads than females. Despite these differences in absolute loads, ratings of

perceived exertion (RPE) were quite similar for males and females at each relative load. In both analyses the 'local' RPEs were relatively higher than the 'central' ratings at 30% and 50% 1RM. This reflected a higher intensity of work than indicated by either oxygen consumption or calculated energy expenditure ( $\text{kcal}\cdot\text{min}^{-1}$ ).

Analyses of the 'pullover' and 'abdominal' units indicated that absolute loads at 10% and 30% stress levels were also different for males and females, the latter moving lighter loads. Despite these absolute load differences, the RPEs for the 10 min exercise duration were quite similar at each relative load. It was found that at the 10% stress level little difference between 'local' and 'central' RPEs for males and females existed. At the 30% stress level, male ratings were slightly higher for both 'local' and 'central' factors. However, local RPE was slightly higher than 'central' RPE, indicating anaerobic pathways becoming more prominent.

These findings support the expectation that variable resistance isotonic exercise will predominantly stress the anaerobic energy pathways; even moving the lightest weight for long periods will not place sufficient demands on the aerobic pathway to affect cardiovascular function.

## RECOMMENDATIONS

Based on these findings it is recommended that:

1. Variable resistance isotonic machinery be used to develop muscular endurance and strength. These units do not lend themselves to development of cardiovascular performance and cannot effectively serve as weight loss devices. However, through correct use it may be possible to maintain present levels of cardiovascular conditioning using this sort of machinery.
2. Manufacturers of this type of equipment need to consult ergonomists or physiologists, psychologists, biomechanicians, orthopaedic surgeons and mechanical engineers before attempting to design such equipment, since incorrect design may cause more harm than benefit.
3. Analysis of this type of equipment should always be holistic, employing the inter-disciplinary fields of ergonomics and the ergonomic method of analysis.
4. Isometric maxima should be generated at as many points as possible through a range of motion in order to more accurately establish the cam radii upon which cam shape is based.
5. A large and more varied population could be utilised in future studies of this nature, thereby reducing any unwanted external influences, and facilitating more definitive statements about this type of research.
6. Metabolic responses to variable resistance isotonic

training need to be more rigorously studied so that more concrete statements as to the effects of the influence of anaerobic and aerobic pathways during this type of activity can be made.

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## APPENDIX I

### HORIZONTAL SHOULDER FLEXION

#### (i) Pectoralis Major

This muscle originates on the medial half of the anterior surface of the clavicle, the whole length of the sternum and the anterior surface of the costal cartilages of the first 6 ribs. It is functionally divided into clavicular and the sternocostal portions. Its insertion is by a flat, 5cm wide tendon, to the outer lip of the bicipital groove of the humerus.

The muscle is innervated by the lateral and medial pectoral nerve; the fibres for the clavicular portion of the muscle are derived from C<sub>5</sub> and C<sub>8</sub>, and those for the sternocostal portion arise from C<sub>7</sub>, C<sub>8</sub> and T<sub>1</sub>.

The two portions of the pectoralis major are capable of acting in combination or independently of each other. As a whole, the muscle takes an active part in the movements of adduction and medial rotation of the humerus. When the arm has been drawn backwards and laterally (extended), the pectoralis major draws it forwards and medially.

#### (ii) Corachobrachialis

This muscle originates from the apex of the coracoid process of the scapula. It inserts midway along the medial border of the shaft of the humerus between the attachments of triceps and brachialis. Its nerve supply is the musculocutaneous nerve from C<sub>5</sub>, C<sub>6</sub>, C<sub>7</sub>. The muscle is located deep beneath the deltoid and pectoralis major muscles.

It acts to draw the arm forwards and medially, especially from a position of extension. When the arm is raised from the side (abducted), it acts with the anterior fibres of the deltoid to prevent sidesway.

#### (iii) Deltoid

This muscle originates on the lateral third of the anterior surface clavicle, the border of the acromion, and the lower edge of the spine of the scapula. It inserts by a short substantial tendon attached to the deltoid tuberosity on the lateral surface of the humerus.

The muscle is innervated by the axillary nerve C<sub>5</sub>, C<sub>6</sub>. It is capable of acting as a whole or in part. The anterior fibres, primarily used in the movement of interest here, co-operate with pectoralis major in drawing the arm forwards and is a potential medial rotator of the humerus.

**(iv) Pectoralis Minor**

This muscle is deep to the pectoralis major. It originates on the lateral surface of ribs three to five, a little to the side from the junction with the costal cartilages. Its fibres pass up and laterally, converging into a flat tendon, attached to the medial border and upper surface of the coracoid process of the scapula. This muscle's anterior surface is contiguous with the pectoralis major muscle. It is innervated by both pectoral nerves C<sub>6</sub>, C<sub>7</sub> and C<sub>8</sub>. The muscle assists serratus anterior in drawing the scapula forwards around the chest wall, or raising the ribs.

**(v) Serratus Anterior**

This muscle originates on the outer surface of the upper nine ribs of the side of the chest, and inserts on the anterior surface of the whole length of the medial border of the scapula.

It is innervated by the long thoracic nerve C<sub>5</sub>, C<sub>6</sub> and C<sub>7</sub>, which descends on the external surface of the muscle. Along with pectoralis minor it draws the scapula forward and is important in all reaching and pushing movements. The upper part of serratus, together with levator scapulae and the upper fibres of trapezius, provide a muscular suspension of the scapula. The lower and stronger fibres of serratus anterior draws the lower angle of the scapula forwards around the chest wall, and assists the trapezius in upward rotation of the scapula.

## APPENDIX II

### KNEE EXTENSION

#### (i) Rectus Femoris

The straight head arises from the anterior inferior iliac spine and the reflected head from the upper margin of the socket of the hip joint in the supra-acetabular groove. It ends in a broad and thick aponeurosis and gradually narrows into a flattened tendon attached to the base of the patella. This is the superficial central part of the quadriceps tendon.

#### (ii) Vastus Intermedius

This muscle arises from the anterior and lateral surface of the upper two thirds of the femoral shaft, and from the lower part of the lateral intermuscular septum. Its fibres end in an aponeurosis on the anterior surface of the muscle; this aponeurosis forms the deep part of the quadriceps femoris tendon and, in addition, is attached to the lateral border of the patella and the lateral condyle of the tibia.

#### (iii) Vastus Medialis

This muscle arises from the medial lip of the lined aspera and the lower part of the intertrochanteric line. Its fibres pass downwards and forwards, and are chiefly attached to an aponeurosis on the deep surface of the muscle which is attached to the medial border of the patella and the quadriceps femoris. An expansion of this aponeurosis reinforces the capsule of the knee joint and is attached below to the medial condyle of the tibia.

#### (iv) Vastus Lateralis

This is the largest of the quadriceps femoris. It arises from the lateral surface of the greater trochanter, the intertrochanteric line, the gluteal tuberosity and the upper half of the lateral lip of the linea aspera. This aponeurosis covers the upper three quarters of the muscle and from its deep surface many additional fibres arise. The muscular mass thus formed is attached to a strong aponeurosis on the deep surface of the lower part of the muscle; this contracts into a flat tendon, attached to the base and lateral border of the patella, and blends with the quadriceps femoris tendon. It gives to the capsule of the knee joint an expansion which descends to the lateral condyle of the tibia and blends with the illiotibial tract.

Thus the tendons of the four muscles unite in the lower part of the thigh to form a common strong tendon attached to the base of the patella. Distal to the patella, the tendon is

continued as the patella tendon which is inserted into the tibial tuberosity.

Superficial fibres run across the patella, while the deep tendon fibres insert into its upper and lateral margins. Mainly fibres of the vastus medialis and a few fibres of the rectus femoris form the medial patellar retinaculum, and fibres of the vastus lateralis and rectus femoris form the lateral patellar retinaculum. Fibres from the iliotibial tract also radiate into the lateral patellar retinaculum. The retinacula extend distally around the patella to the tibial condyles. Quadriceps femoris are supplied by the femoral nerve. L<sub>2</sub> - L<sub>4</sub>.

### **Actions**

The quadriceps femoris extends the leg upon the thigh. The rectus femoris also assists in flexing the thigh on the pelvis, or, if the thigh is flexed, it helps to flex the pelvis; it is, however, remarkably quiescent in standing. The rectus can of course flex the hip and extend the knee simultaneously.

The lower fibres of the vastus medialis contract particularly during the terminal phase of extension of the knee joint to retain the patella in its groove on the patellar surface of the femur, by counteracting the natural tendency to lateral displacement of the patella, which is attributable to the angulation between the shaft of the femur and the bones of the leg.

## APPENDIX III

### VERTICAL SHOULDER EXTENSION

#### (i) Latissimus Dorsi

This is a large, triangular, flat muscle, which is the largest muscle in humans. The thoracic portion arises from the spinous processes of the 7th - 12th vertebrae. The iliac part arises from the thoracolumbar fascia and the posterior third of the iliac crest. The costal portion arises from the 10th - 12th ribs.

From this extensive attachment the fibres pass laterally with varying degrees of obliquity, the thoracic ones horizontally, the costal portion obliquely upwards and the iliac section almost vertically upwards, to converge into a thick fasciculus. The muscle is wrapped around the lower border of the teres major, curving around its anterior surface. Here it ends in a quadrilateral tendon, about 7 cm long, which passes in front of the tendon of the teres major and is attached to the bottom of the intertubercular sulcus of the upper humerus. On account of the way in which the muscle curves around the lower border of the teres major, its constituent fibres are spiralised, consequently the fibres which are lowest at the mid-line attachment are attached highest on the humerus, while the highest mid-line fibres pass into the lower part of its tendon.

It is innervated by the thoracodorsal nerve from the posterior cord of the brachial plexus C<sub>6</sub>, C<sub>7</sub> and C<sub>8</sub>.

The latissimus dorsi is active in movements of adduction, extension and especially medial rotation of the humerus. It lowers the raised arm and adducts it. When the arm is abducted, it pulls it backward and medially. It acts with the sternocostal portion of pectoralis major and teres major to depress the raised arm against resistance. It is active in the backward swinging of the arm and is said to take part in all violent expiratory movements such as coughing or sneezing.

#### (ii) Teres Major

This muscle arises from the lateral border of the scapula near the inferior angle, from which the fibres are directed upwards and laterally and end in a flat tendon about 5 cm long, which inserts on the crest of the lesser tubercle. Teres major is innervated by the lower subscapular nerve C<sub>6</sub> and C<sub>7</sub>. Its main function is extension of the arm toward the mid-line, a movement requiring extension and simultaneously a small medial rotation. It is particularly prominent if the arm has previously been flexed at the shoulder and slightly abducted.

### (iii) Triceps Brachii

The triceps in the extensor compartment of the upper arm, is of large size and arises by 3 heads - the long, the lateral, and the medial - hence its name.

The lateral head arises by a flattened tendon from a narrow ridge on the posterior surface on the shaft of the humerus, from the lateral surface of the humerus and in its distal part from the intermuscular septum. The long head arises by a flattened tendon from the infraglenoid tubercle of the scapula and the muscle fibres pass downwards and extend distally in front of teres minor and behind teres major. The medial head arises from the lateral border of the humerus, and the lateral intermuscular septum. Proximally it originates just beneath the greater tubercle and ends distally in the region of the lateral intermuscular septum.

The 3 heads fuse in a flat common-end tendon, which is inserted on the olecranon process of the ulna and the posterior wall of the joint capsule. The long head of the triceps brachii acts on 2 joints (shoulder, elbow) while the other heads act only on one joint (elbow).

The triceps brachii are innervated by the radial nerve C<sub>6</sub>, C<sub>7</sub> and C<sub>8</sub> with separate branches supplying the three heads.

The triceps is the great muscle of extension of the forearm on the arm at the elbow joint. When the flexed arm is extended at the shoulder joint, the long head of the muscle may assist in drawing the humerus backwards and in adducting it to the thorax. The long head supports the lower part of the capsule of the shoulder joint, when the arm is raised from the side.

### (iv) The Deltoid

This muscle is divided into 3 parts:

- (a) The clavicular (anterior) portion arises from the lateral third of the clavicle.
- (b) The spinal (posterior) portion arises from the lower border of the spine of the scapula and
- (c) The acromial (lateral) portion from the acromion.

It inserts by a short substantial tendon attached to the deltoid tuberosity on the lateral surface of the humerus.

This muscle is innervated by the axillary (circumflex) nerve C<sub>4</sub> - C<sub>6</sub>. The clavicular and spinal fibres are able to adduct the arm after it has been lowered to a third of its range of movement. The clavicular fibres, aided by some of the acromial fibres, can produce flexion of the humerus, and the spinal fibres, helped by other acromial fibres produce extension of humerus. The clavicular fibres can produce medial rotation in an arm which is adducted and laterally rotated, while the spinal fibres can produce lateral rotation in a medially rotated arm.

#### **(v) Pectoralis Major**

This muscle originates on the medial half of the anterior surface of the clavicle, the whole length of the sternum and the anterior surface of the costal cartilages of the 1st to 6 ribs. It is functionally divided into clavicular and sternocostal portions. Its insertion is by a flat 5 cm wide tendon, to the outer lip of the bicipital groove of the humerus.

The muscle is innervated by the lateral and medial pectoral nerve; the fibres for the clavicular portion of the muscle are derived from C<sub>5</sub> and C<sub>8</sub> and those for the sternocostal portion arise from C<sub>7</sub>, C<sub>8</sub> and T<sub>1</sub>.

The 2 parts of the muscle are capable of acting in combination or independently of each other. When the arm has been extended, the pectoralis major draws it forward and medially. When the arm is swung forwards and medially, the sternocostal fibres take no part in the movement, which is carried out by the clavicular fibres, acting with the anterior fibres of the deltoid and with coracobrachialis. When the opposite movement is resisted (extension), the sternocostal portion helps latissimus dorsi and teres major.

#### **(vi) Serratus Anterior**

This muscle arises by 9 slips from the 1st - 9th ribs. The insertion of the muscle extends from the superior to the inferior angles along the entire medial margin of the scapula. The muscle is innervated by the long thoracic nerve C<sub>5</sub>, C<sub>6</sub> and C<sub>7</sub>, which descends on the external surface of the muscle. This muscle pulls the scapula towards the front, a movement essential for flexion of the arm. The superior and inferior portions together press the scapula into the thorax. The inferior portion rotates the scapula laterally and pulls the inferior angle laterally and forward.

#### **(vii) Coracobrachialis**

Arises from the coracoid process together with the short head of the biceps brachii. It is inserted on the medial surface of the humerus on the continuation of the crest of the lesser tubercle.

It is innervated by the musculocutaneous nerve C<sub>6</sub> and C<sub>7</sub>. It draws the arm forwards and medially, especially from a position of extension. When the arm is raised from the side, it acts with the anterior fibres of the deltoid to prevent side-sway.

#### **(viii) Brachialis**

This muscle arises from the distal half of the anterior

surface of the humerus and the intermuscular septa. It is inserted into the ulna tuberosity and the joint capsule. It is innervated by the musculocutaneous nerve C<sub>5</sub> and C<sub>6</sub>. A small lateral part of the muscle is supplied by the radial nerve C<sub>5</sub> and C<sub>6</sub>. It is a single joint muscle and is the most important flexor of the elbow joint, independent of pronation or supination of the forearm. Its full power is exerted in lifting a heavy load. In such a movement there is also slight extension of the shoulder joint.

**(ix) Extensor Digitorum**

This has a flattened origin from the lateral epicondyle of the humerus, the radial collateral ligament and the annular radial ligament. With its tendon it forms the dorsal aponeurosis of the 2nd to 5th fingers. It is innervated by the deep branch of the radial nerve C<sub>6</sub>, C<sub>7</sub> and C<sub>8</sub>. It is the strongest dorsiflexor of the wrist and the mid-carpal joints and it acts, too, as an ulnar adductor. It extends and spreads the fingers.

**(x) Biceps Brachii**

Arises with its long head from the supraglenoid tubercle and with its short head from the coracoid process. Both heads usually join, at the level of insertion of the deltoid, into the biceps muscle, which again terminates with two tendons. The stronger tendon is inserted into the radial tuberosity. The other flattened tendon, whose fibres form the continuation of part of the short head, radiates into the fascia of the forearm on the ulnar side. The long head traverses the shoulder joint and extends along the intertubercular humerus. In its action it uses the head of the humerus as a fulcrum.

This muscle is innervated by the musculocutaneous nerve C<sub>5</sub> - C<sub>6</sub>. The biceps brachii acts on two joints. With its long head it abducts the arm and rotates it medially. The short head is an adductor. Both heads are involved in the flexion of the shoulder joint. It is also a flexor and a strong supinator of the elbow joint.

**(xi) Brachioradialis**

This muscle arises from the lateral supracondylar crest of the humerus and the intermuscular septum. It is inserted into the radial surface of the styloid process of the radius. This muscle is innervated by the radial nerve C<sub>5</sub> - C<sub>6</sub>.

This muscle acts only on a single joint. It brings the forearm into the midposition between pro- and supination. In this position it acts as a flexor. It has a minimal flexor action in slow movements and in the supinated forearm.

## APPENDIX IV

### SPINAL FLEXION

#### (i) Internal Oblique

This muscle arises by fibres from the lateral two-thirds of the upper surface of the inguinal ligament, from the anterior two-thirds of the ventral segment of the iliac crest, and from the thoracolumbar fascia. The posterior fibres pass upwards and laterally to the inferior borders of the lower three or four ribs, and are there continuous with the internal intercostal muscles. The uppermost fibres from the inguinal ligament, paler in colour, arch downwards and medially across, and becoming tendinous, are attached with the corresponding part of the aponeurosis of the transversus abdominis to the crest and the medial part of the pubis, forming the conjointed tendon.

Nervous supply of this muscle is by the ventral rami of the lower six thoracic and the first lumbar spinal nerves.

#### (ii) External Oblique

This muscle curves around the lateral and anterior parts of the abdomen and is the largest and the most superficial of the three flat muscles in this region. It arises from the external surfaces of the lower eight ribs, by eight fleshy slips. These slips are arranged in an oblique line which extends downwards and backwards, the upper slips being attached close to the cartilages. From these attachments the fibres diverge as they pass to their insertions.

Those from the lower two ribs pass nearly vertically downwards and are attached to the anterior half of the outer lip of the ventral segment of the iliac crest; the middle and upper fibres, directed downwards and forwards, end in an aponeurosis, and then inclining laterally to the anterior superior iliac spine. The posterior muscle of the border is free.

This muscle is innervated by the ventral rami of the lower six thoracic spinal nerves.

#### (iii) Rectus Abdominis

This is a long strap muscle, broader above, which extends along the whole length of the front of the abdomen, separated from its fellow by the linea alba. It arises by two tendons; the lateral and the larger is attached to the crest of the pubis; the medial interlaces with its fellow and is connected with the ligamentous fibres covering the symphysis pubis. This muscle is attached by three slips of unequal size into the fifth, sixth, and seventh costal cartilages.

The muscle fibres of the rectus are interrupted by three

fibrous bands, named tendinous intersections; one is usually situated opposite the umbilicus, another opposite the free end of the xiphoid process, and a third about midway between the xiphoid process and the umbilicus. These intersections pass transversely or obliquely across the muscle in a zig-zag course.

Innervation of rectus abdominis is by the ventral rami of the lower six or seven thoracic spinal nerves.

**(iv) Iliocostalis Lumborum**

This muscle extends from the sacrum, external lip of the iliac crest and the thoracolumbar fascia to the costal process of the upper lumbar vertebrae and the lower six to nine ribs.

This muscle is innervated by the dorsal rami (C<sub>4</sub> - L<sub>3</sub>).

**(v) Iliocostalis Thoracis**

This muscle stretches from the lower six ribs to the upper six ribs, and is innervated by the dorsal rami (C<sub>4</sub> - L<sub>3</sub>).

**(vi) Longissimus Thoracis**

Arises from the sacrum, the spinous processes of the lumbar vertebrae and the transverse processes of the lower thoracic vertebrae and extends to the first or second ribs. It is attached medially to the accessory processes of the lumbar vertebrae and to the transverse processes of the thoracic vertebrae. Laterally it is attached to the ribs, the costal processes of the lumbar vertebrae and the deep lamina of the thoracolumbar fascia. Innervation is by the dorsal rami (C<sub>4</sub> - L<sub>3</sub>).

**(vii) Spinalis Thoracis**

Has its origin on the spinous processes of the upper lumbar and lower thoracic vertebrae and inserts on the spines of the upper thoracic vertebrae. Its nerve supply is from the dorsal rami (C<sub>1</sub> - C<sub>8</sub>).

**Actions**

The abdominal muscles provide firm pressure on the abdominal viscera, holding them in position and oppose the action of gravity on them in the erect and sitting positions. This function is principally dependent on the normal contraction of the oblique muscles, especially the internal oblique.

When the pelvis is fixed, the recti, and to a lesser extent the oblique of the two sides, acting together, bend the trunk forwards and flex the lumbar part of the vertebral column; when the thorax is fixed, they draw the front of the

pelvis upwards and have the same effect as before on the vertebral column. If the muscles on only one side act, the trunk is bent towards that side. In addition, the external oblique tends to turn the front of the abdomen towards the opposite side, and the internal oblique turns it to the same side.

EMG studies suggest that in most movements of the trunk, whether in the sitting or the standing position, the abdominal musculature is little involved, unless considerable resistance is applied. All activity ceases in the supine position, but the recti in particular at once spring into action when merely the head is raised. Further flexion brings the obliques into action, but less forcibly.

## APPENDIX V

### HIP ABDUCTION

#### (i) Gluteus Medius

This is a broad, thick muscle on the outer surface of the pelvis. Its posterior third is covered by gluteus maximus; its anterior two thirds is superficial and covered by a strong layer of deep fascia. It arises from the outer surface of the ilium between the iliac crest and posterior gluteal line above, and the anterior gluteal line below; it also arises from the strong fascia superficial to its upper part. The fibres converge into a flattened tendon, which is attached to the oblique ridge slanting downwards and forwards on the lateral surface of the greater trochanter. The posterior edge of gluteus medius is sometimes blended with piriformius. Innervation is by the superior gluteal nerve, L<sub>5</sub>-S<sub>1</sub>.

#### (ii) Gluteus Minimus

This is the smallest muscle of the gluteal group, and is deep to the medius. It is fan-shaped, arising from the outer surface of the ilium between the anterior and inferior gluteal lines, and, behind, from the margin of the greater sciatic notch. The fibres converge to the deep surface of an aponeurosis, and this ends in a tendon attached to a ridge laterally situated on the anterior surface of the greater trochanter, and gives an expansion to the capsule of the hip joint. The muscle may be divided into anterior and posterior parts. Nervous supply is by the superior gluteal nerve L<sub>5</sub>-S<sub>1</sub>.

#### (iii) Tensor Fascia Latae

This arises from the anterior 5cm of the outer lip of the iliac crest, the lateral surface of the anterior superior iliac spine, and part of the border of the notch below it, between gluteus medius and sartorius. It descends between and is attached to, the two layers of the iliotibial tract of the fascia lata and ends about the junction of the middle and the upper third of the thigh.

