CHAPTER 1

GENERAL INTRODUCTION

1.1 THREE DIMENSIONAL (3D) MUSCULOSKELETAL MODELLING

Biomechanics is the study of motion and its causes in living things. Within the application of sport, exercise and rehabilitation science, biomechanics provides key information on the most effective and safest movement patterns, equipment, and the relevant exercises to improve human movement (Knudson, 2007). Thus, the ultimate goal of exercise and sport biomechanics is performance improvement and a secondary goal is injury prevention (McGinnis, 2005). In biomechanical modelling the human body is treated as a mechanical system of linkages and masses, activated by muscles that span joints (Kroemer *et al*., 2001).

A computer model of the human musculoskeletal system is a mathematical description of the body in motion compiled into a computer programme (Luttgens *et al*., 1992). The advancement in computer technology and data processing capability has allowed the improvement of modelling software to a point where dynamic problems can now be simulated and analysed in a digital environment (Zenk *et al*., 2005; Kim & Martin, 2007; Wagner *et al*., 2007). Furthermore, computer simulations allow for the exploration of the limitations of human movement systems without endangering human subjects (Luttgens *et al*., 1992).

Mathematical and computer modelling is suitable for a wide variety of applications such as the design, production and alteration of medical equipment (prostheses, orthopaedic and orthodontic devices) as well as sports and training equipment (Alexander, 2003; Kazlauskiené, 2006). With the capability to simulate musculoskeletal human models interacting with mechanical systems many questions concerning the effects of the resistance training equipment on the body can be studied. In addition, computer simulation models permit the study of the complex interactions between biomechanical variables (Kenny *et al.*, 2005).

From a biomechanics perspective, the design of some resistance training machines or exercise equipment are more sound than others, in that they can be adjusted to accommodate different limb lengths and user sizes. The quality of machines can vary widely (Beachle & Earle, 2008).

Design of exercise equipment is a complex task and needs to consider a series of biomechanical, anthropometric and ergonomics factors. Furthermore, there is inevitably increased loading on certain parts of the body during exercise due to the repetitive nature of exercises. Improvement in equipment design could reduce these hazards and offset such a negative effect on the body (Dabnichki, 1998).

1.2 PROBLEM FORMULATION

The public's interest in becoming physically fit has created a global multi-million dollar industry that does not always promote items or services that are safe, effective or necessary (Prentice, 2003). When considering the results of scientific, popular and patent database searches it is evident that very few of the commercially off the shelf (COTS) pieces of exercise equipment are subjected to any formal scientific testing and evaluation in order to ensure equipment safety and efficacy.

Thus, the motivation for this study originates from a concern for the quality and apparent lack of scientific data that supports exercise equipment evaluation, design and specification. Currently, there is no standard biomechanical evaluation protocol for exercise equipment and more specifically resistance training equipment. Therefore, a need exists to develop and implement basic biomechanical evaluation protocols for exercise equipment. As a result the safety of the exerciser will be maximised and the efficacy of the exercise will also be enhanced.

1.3 GOALS AND OBJECTIVES

1.3.1 Goal

The goal of this study is to evaluate whether 3D musculoskeletal modelling is effective in assessing the safety and efficacy of resistance training equipment. The focus of the evaluation is on the biomechanical and anthropometric considerations of the end-user.

1.3.2 Objectives

The study aims to achieve the goal through its objectives, which are:

- To develop an evaluation protocol through computer modelling for resistance training equipment. The protocol will include:
    - anthropometric evaluation,
    - biomechanical evaluation,
- To implement the evaluation protocol on four pieces of resistance training equipment.
- Identify potential risk for musculoskeletal injury.
- Make recommendations on how the equipment could be improved with regards to design in order to maximise safety and exercise efficacy.
- Make recommendations regarding limitations of the evaluation protocol. Evaluate if the protocol is sensitive enough to indicate injury risk and/ or limitations in equipment design.

1.4 HYPOTHESIS

A hypothesis is a statement in which an assumed relationship or difference between two or more phenomena or variables is postulated (Mouton & Marais, 1990). In the light of the goal of this study, the following research hypothesis is formulated:

3D musculoskeletal modelling focusing on biomechanical and anthropometric considerations of the end-user is effective in evaluating the overall design of resistance training equipment.

Sub-hypotheses are formulated from the main hypothesis:

- Meaningful recommendations can be made regarding improving the safety of exercise equipment; and
- Meaningful recommendations can be made regarding improving the efficacy of training on exercise equipment.
- Poor accommodation of the user by exercise equipment will put the exerciser at increased risk for injury.

1.5 RESEARCH APPROACH

The approach of this research is that of an evaluation study, combining digital parametric modelling with an analytical research focus.

1.5.1 Type of Research

The type of research that the researcher will make use of will be applied research. De Vos *et al*. (1998: 20) define applied research as "…*geared to the development of knowledge and technology with a view to achieving meaningful intervention.*" This research can be classified as applied research because the researcher will gain knowledge and insight with regards to the various pieces of exercise equipment and use the information to make suggestions on how to improve the design of the exercise equipment.

Descriptive research is a study of status that is widely used in education and the behavioural sciences. Its value is based on the premise that problems can be solved and practices improved through objective and thorough observation, analysis, and description (Thomas & Nelson, 1990). Several techniques or methods of problem solving fall into the category of descriptive research. In addition, there are various forms of descriptive studies (Thomas & Nelson, 1990;

Babbie & Mouton, 2001). This study will consist of an evaluative case study due to the fact that this study will involve the collection of data, and the analysis and reporting of results.

Data collection will primarily take place by means of digital parametric modelling and therefore quantitative research methods will be used. Quantitative research is a type of conclusive research involving large representative samples and reasonably structured data collection procedures. A quantitative study requires that a large amount of data is collected and then expressed in numbers (Struwig & Stead, 2001).

1.6 STRUCTURE OF THE THESIS

Herewith follows a detailed description of the initial and subsequent chapters of the thesis:

Chapter 1: General introduction, briefly describes biomechanics modelling, specifically computer modelling of the human musculoskeletal system. This chapter also discusses the important role that this type of modelling can play in ensuring the efficacy and safety of exercise equipment. Further it provides the problem formulation, goals, hypotheses and research approach of the study.

Chapter 2: Overview (Resistance training), reports on resistance training and resistance training equipment (history, biomechanics, available equipment, injuries and equipment design).

Chapters 3 - 6: Implementation of 3D musculoskeletal modelling with the focus on the biomechanical and anthropometric considerations of the end-user on four pieces of resistance training equipment,

- Seated biceps curl (Chapter 3)

  This study presents the musculoskeletal modelling of three anthropometric cases while exercising on a commercially available seated biceps curl resistance training machine. The biceps curl exercise is a commonly used, predominantly single joint open-kinetic-exercise used to isolate the biceps muscles. A 3D musculoskeletal full body model was created using LifeModeler™ software and incorporated into a multibody dynamics model of the seated biceps curl resistance training machine modelled in MSC ADAMS.

- Abdominal crunch (Chapter 4)

  This study presents the musculoskeletal modelling of three anthropometric cases while exercising on a commercially available abdominal crunch resistance training machine. The abdominal crunch resistance training exercise is one of many available exercises, devices or equipment available to strengthen the muscles of the abdominal region such as the Rectus abdominis and Oblique (internal and external) muscles. A 3D musculoskeletal full body model was created using LifeModeler™ software and incorporated into a multibody dynamics model of the abdominal crunch resistance training machine modelled in MSC ADAMS.

- Seated row (Chapter 5)

  This study presents the musculoskeletal modelling of three anthropometric cases while exercising on a commercially available seated row resistance training machine. The seated row resistance training exercise is an exercise commonly used to strengthen the musculature of the upper back. A 3D musculoskeletal full body model was created using LifeModeler™ software and incorporated into a multibody dynamics model of the seated row resistance training machine modelled in MSC ADAMS.

- Chest press (Chapter 6)

  This study presents the musculoskeletal modelling of three anthropometric cases while exercising on a commercially available open-kinetic chain chest press resistance training machine. The chest press resistance exercise is a popular exercise used to primarily strengthen the musculature of the chest. A

3D musculoskeletal full body model was created using LifeModeler™ software and incorporated into a multibody dynamics model of the chest press resistance training machine modelled in MSC ADAMS.

Chapter 7: Summary, general conclusions and recommendations, provide a summary, conclusions on the interpretations of the findings, and indications for further research.

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CHAPTER 2

OVERVIEW: RESISTANCE TRAINING

2.1 EXERCISE AND EXERCISE EQUIPMENT

The general publics' growing awareness of the importance of exercise and wellness has led to an exercise-fitness revolution. Enthusiasm for exercise and fitness is at unprecedented levels with millions of people spending countless hours and millions of Rands on sport and exercise (Prentice, 2003). Increased mechanization and the incidence of hypokinetic diseases are two important factors that have contributed to the emphasis on fitness. With increased mechanization, many tasks that once required physical work and considerable amount of time can now be accomplished very quickly by pushing a button or setting a dial (Hockey, 1996).

Consequently the exercise equipment manufacturing industry has rapidly expanded over the past few years largely due to the amplified eagerness for exercise and fitness and thus equipment demand. Not only has sales of conventional exercise equipment grown enormously but there has also been an escalation in the number of new exercise equipment being designed and marketed. According to Beachle and Earle (2008) the machine age is upon us, and we have a wide variety of exercise devices to choose from, depending on our likes and dislikes. The two primary categories of exercise training equipment, include cardiorespiratory and resistance training equipment.

2.2 RESISTANCE TRAINING

2.2.1 Definition

Resistance training refers to a method of conditioning designed to overload the musculoskeletal system, leading to accelerated enhancement of muscle strength (Fleck & Kraemer, 1997).

The term resistance training encompasses a wide range of resistive loads and a wide variety of training modalities, including, free weights (barbells and dumbbells), weight machines, elastic tubing, medicine balls, stability balls, and body weight (Howley, 2007). Resistance training should be distinguished from the competitive sports of weightlifting, powerlifting and bodybuilding (Vaughn, 1989; Howley, 2007). Competitive weightlifting is primarily encompassed by two distinct sports (1) powerlifting, which includes the squat, bench press and deadlift movements; and (2) weightlifting which includes the overhead snatch and clean-and jerk lifts which are contested in the Olympic Games (Vaughn, 1989; Chui *et al., 2008*).

2.2.2 Resistance training equipment

Resistance training equipment can be divided into free weights (barbells and dumbbells), machines (plate loaded, weight stack and isokinetic) or other equipment (elastic tubing, medicine balls, etc.).

A virtual cornucopia of resistance training machines are found in today's market (Beachle & Earle, 2008). Weight training machines are designed to train all the major muscle groups and can be found in most fitness centres (Howley, 2007). They are generally more expensive than free weights and often limit the user to single-joint movements in fixed planes of motions. They do not require the proprioception, balance, and coordination required by free weights, but allows the user to isolate some areas of the body more easily. Many devices utilise a weight stack connected to a lever by chains or cables. Less expensive models require weight plates to be added to provide resistance (Beachle & Earle, 2008).

Although many different types of resistance training machines are currently available this study focuses on machines that use a movable external resistance such as a weight stack. In general these machines are somewhat like free weights in that the external resistance is constant (Figure 2.1).

Many machines alter the resistance encountered by the muscles with a system of cams, levers, or pulleys, resulting in a variable-resistance system. Some manufacturers attempt to increase the resistance during a range of motion in an attempt to mimic the human strength curves of various joints or physical movements. Strength curves are variable, however, and in some instances the strength curves of the machines are not identical with those of the human body (Maud & Foster, 2006).

Choosing an appropriate training method can make a considerable difference in the outcome of the resistance training programme. It is also probable that the choice of training mode (type of equipment) can influence adaptations to a training programme (Stone *et al.,* 2000). Recently emphasis has been placed on “functional” resistance training. Such training is supposed to replicate the body’s natural movements and therefore the user could gain more benefits because of the influence on activities of daily living as well as sporting performance. In addition, isolateral training, allows the user to move both limbs at the same time, one at a time, alternating, or with different weights for each (Life Fitness, 2007).

Simultaneous with the growth in popularity of resistance training among athletes and the general public, there has been growth in companies producing resistance training equipment. One in particular made a dramatic impact: Nautilus. The Nautilus equipment design and marketing strategy created a different image of resistance training. The attractive and sophisticated machines placed in clean, well lit surroundings were a far cry from the rusty barbells and dumbbells typically found in the less-than-aesthetic surroundings of traditional weight rooms. These changes, along with others by competing equipment companies, made resistance training not only an acceptable activity, but a trend-setting one (Beachle & Groves, 1992).

Today, in South Africa the primary suppliers of resistance training equipment are Technogym and Fitness World.

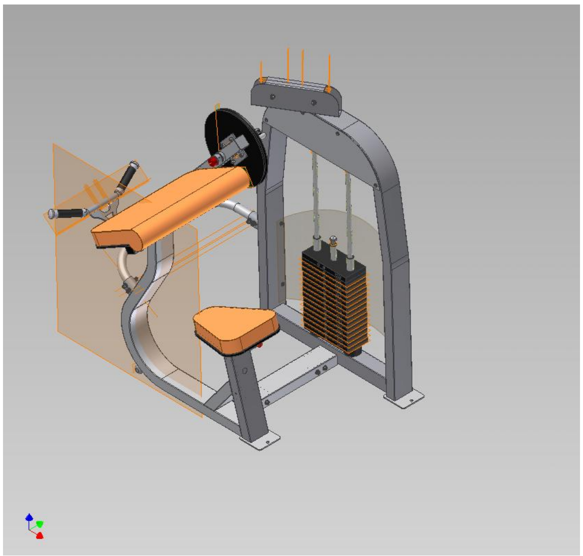

Figure 2.1: Example of a seated biceps curl machine

2.2.3 History of resistance training

Texts regarding resistance training date back to antiquity. Perhaps the earliest record in existence of any form of resistance exercise is a drawing on the wall of a funerary chapel in Beni-Hassan in Egypt. This drawing, done approximately 4500 years ago depicts three figures in various postures of raising overhead what appear to be heavy bags. The bags are lifted in what would now be termed a one-handed swing. Another example of early resistance training is that of athletes using halteres for resistance training and broad jump during the classical period in Greece, halteres being the ancestors of our modern dumbbells (Figure 2.2) (Pearl & Moran, 1986).

Although demonstrations of strength have captured the interest and imagination of people as far back as ancient times, the merits of activities designed to develop strength have not always been well understood or appreciated. For many years it was believed that training with weights provided few if any benefits and, in fact, would result in poor levels of flexibility and impairs neuromuscular coordination. A special concern was that training with weights would result in tremendous increases in muscular size. This was a primary concern among women, many of whom had been led to believe that having a strong-looking physique or being strong, was not feminine. These myths kept many from enjoying the benefits of weight training. It was not until the 1930s, when two physical therapists, DeLorme and Wadkins, reported successful results using weight training in the rehabilitation of arm and leg injuries of soldiers, that the “renaissance” in attitude about weight training began (Beachle & Groves, 1992).

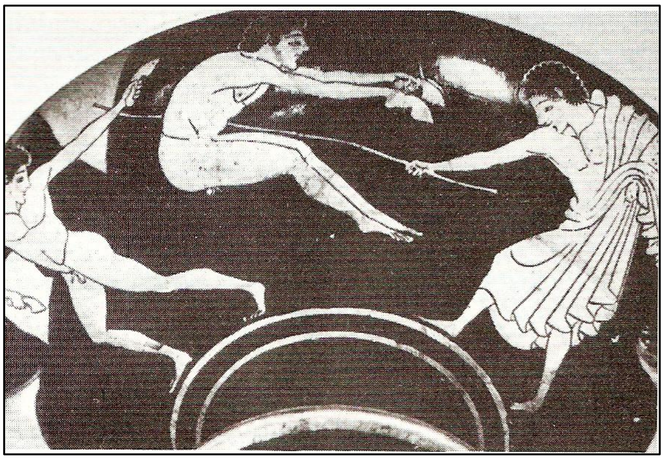

Figure 2.2: Drawing on a plate from the classical period in Greece shows two athletes using halteres, the ancestors of our modern dumbbells. Halteres were used for various standard resistance exercises and broad jumping (Pearl & Moran, 1986).

2.2.4 The future of resistance training

A comprehensive exercise programme should include resistance training, which has its own unique advantages and is recommended by national health organizations such as the American College of Sports Medicine (Kang, 2008). Although the primary outcome of resistance training is improved strength and muscular endurance, a number of health benefits are also derived from this form of exercise. Resistance exercise builds bone mass, thereby counteracting the loss of bone mineral and risk of fractures through falls as one age. This form of training also lowers blood pressure in hypertensive individuals, reduces body fat levels, and may prevent the development of low back syndrome (Heyward, 2006). Furthermore, programmes incorporating strength training as an integral part of physical conditioning have also been shown to improve performance in ergonomic tasks, such as lifting weighted boxes to different heights. These types of observations indicate that resistance training can have a transfer-of-training effect that results in a change in functional ability and capacity (Stone *et al.,* 2000).

The current popularity of resistance training is so extraordinary that only those who were alert to such facts as the growing use of weights for sports, the changing attitudes about strength as an aspect of femininity and the increasing interest in fitness, could have foreseen what has now come to pass (Pearl & Moran, 1986). Traditionally, resistance training was used primarily by adult athletes to enhance sport performance and increase muscle size. Today, resistance training is recognized as a method of enhancing the health and fitness of men and women of all ages and abilities (Howley, 2007). The popularity of resistance training is clearly evidenced by the extensive growth of fitness centres and sales of resistance exercise equipment for home use. The increased popularity of, and participation in body-building competitions worldwide is also indicative of the level of interest in benefits derivable from resistance training (Vaughn, 1989; Lou *et al*., 2007).

Although new pieces of exercise equipment are continuously being designed and produced the “core” pieces of resistance training equipment such as the chest press and leg extension machines have not changed significantly over the past few years. It does however appear as if the future trends of resistance training equipment will be towards sleeker designs, user friendliness as well as the incorporation of the computer or electronic technology.

2.2.5 Biomechanics of resistance training

Knowledge of musculoskeletal anatomy and biomechanics is important for understanding human movements, including those involved in sports and resistance exercise (Beachle & Earle, 2008). Load carrying is an important aspect of resistance training (Johnson, 2007). Many traditional resistance training exercises revolve around the raising and lowering of weights. The weight is often a combination of an external resistance and a portion of the body (Reiser *et al*., 2007). Lifting of loads require an initial isometric muscular contraction to overcome inertia followed by a dynamic muscular contraction as the load is moved (Johnson, 2007).

Within this typical paradigm, the external resistance begins a repetition from a rested position and is moved vertical, where it again comes to rest. The external resistance is then lowered under control back to the starting position, where an ensuing repetition may be performed. Thus, begins and ends with zero velocity of the person and any external resistance. The majority of the movement is usually in the vertical direction in order to take advantage of the resistance supplied by the force of gravity. However, because linear motion at the hand, foot, or other contact point is the result of angular motion at the joint or multiple joints in some exercises, there is often accompanying horizontal motion with the vertical motion (Reiser *et al.,* 2007).

Linear motion can be defined as the straight line progression of an object as a whole with all its parts moving the same distance in the same direction at a uniform rate or speed. While angular or rotary motion is typical of levers and occurs when any object acting as a radius moves about a fixed point. Most human body segment motions are angular movements in which the body part moves in an arc about a fixed point. The axial joints of the skeleton act as fixed points for rotary motion in the segment (Hamilton *et al.,* 2009).

Even though the path of motion of the body and external resistance may be consistent from repetition to repetition, several factors exist that will influence the magnitude and direction of the forces required to move the external resistance during the course of the exercise (Reiser *et al*., 2007). Muscle strength is often defined as the maximum force or tension generated by a muscle or muscle groups (McArdle *et al*., 1996). Force is any pushing or pulling action that causes movement. The effect produced when a force causes rotation is called torque (T). It is the product of the magnitude of the force (F) and the force arm / moment arm (FA), which is the perpendicular distance from the axis to the direction of the application of that force ($T = F \cdot FA$) (Figure 2.3) (Howley, 2007). There are several biomechanical factors involved in the manifestation of human strength including the force generation properties of the muscles, the anatomical features of the skeletal system (e.g. anthropometric properties, muscle paths) and the underlying neuronal control system (Erdemir *et al*., 2007).

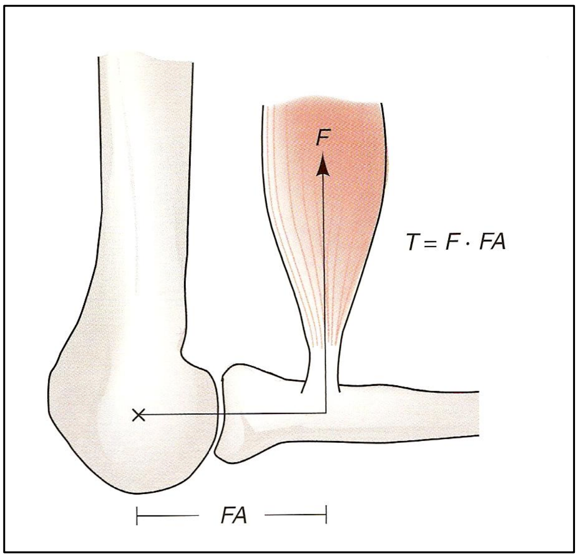

Figure 2.3: Force (*F*) and moment arm (*FA*) of the biceps brachii (Howley, 2007).

All else being equal, the force a muscle can exert is related to its cross-sectional area (Beachle & Earle, 2008). In addition, various muscles have different shapes and their fibres may be arranged differently in relation to each other and to the tendons to which they join. The shape and fibre arrangement play a role in the muscle's ability to exert force and the range through which it can effectively exert force on the bones to which it is attached (Hamilton *et al.,* 2009). There is also an optimum length at which a muscle, when stimulated, can exert maximum tension (Luttgens *et al.,* 1992). A muscle can generate most force around its resting length due to the fact that a maximal number of cross-bridge sites are available between the actin and myosin filaments (Figure 2.4) (Beachle & Earle, 2008).

Another important factor to consider is the muscle's angle of pull, the muscle's angle of pull changes with every degree of joint motion and consequently so does the sizes of the horizontal and vertical components. These changes have a direct bearing on the effectiveness of the muscle's pulling force in the bony lever. The larger the angle between 0 degrees and 90 degrees, the greater the vertical component and the less the horizontal component (Luttgens *et al.,* 1992; Hamilton *et al.,* 2009). Neural control affects the maximal force output of a muscle by determining which and how many motor units are involved in a muscle contraction as well as the rate at which the motor units are fired (Beachle & Earle, 2008).

Lastly another consideration in determining the force production of a muscle is the force-velocity relationship. As the speed of a muscular contraction increases, the force it is able to exert decreases. The velocity of contraction is maximal when the load is zero and the load is maximal during eccentric contraction (Luttgens *et al.,* 1992; Hamilton *et al.,* 2009).

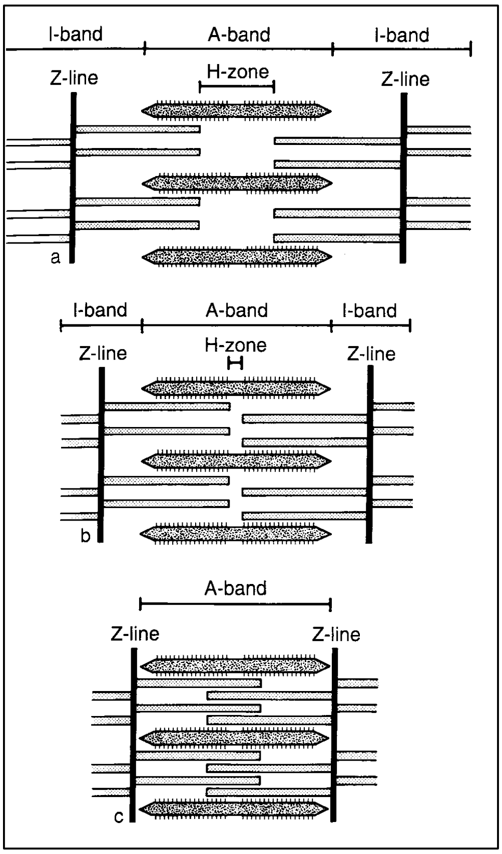

Figure 2.4: Contraction of a myofibril. (a) In stretched muscle, the I-bands and H-zone are elongated, and there is low force potential due to reduced cross-bridge-actin alignment. (b) When muscle contracts (here, partially), the I-bands and H-zone are shortened. There is high force potential due to optimal cross-bridge-actin alignment. (c) With completely contracted muscle, there is low force potential due to reduced cross-bridge-actin alignment (Beachle & Earle, 2008).

Cardiovascular fitness and muscular strength are substantially higher in men compared to women. In men upper body strength is ~ 100% higher and lower body strength is ~ 50% higher (Lynch *et al.*, 1999). However, there are no differences in the “quality” of muscle between sexes and that the observed difference in absolute muscle strength is simply related to the quantity of muscle mass (McArdle, 1996; Johnson, 2007).

2.2.6 Resistance training equipment design

Machines used for resistance training may not actually utilize weights of any kind. For example, air compression cylinders, hydraulic mechanisms, springs, or elastic cables may provide resistance to movement. Of the vast variety of machines currently available for consumer use, however, those most commonly found in public exercise facilities are truly weight machines, that is, their use involves the lifting of weight-plates as part of a weight “stack” (Vaughn, 1989).

From a biomechanics perspective some machines are more sound than others, in that they can be adjusted to accommodate different limb lengths and user sizes. The quality of machines can vary widely (Beachle & Earle, 2008). Equipment design must be regenerative in nature. Designers have not only an obligation to comply with the regulations of appropriate governing bodies but also the responsibility for the safety and comfort of the users. Unfortunately these guidelines mainly address equipment used by various sporting codes with little or no enforceable guidelines for resistance training equipment. Mandatory regulations would enhance the quality of fabrication as well as augmenting the enjoyment of users, secure in the knowledge that real injury risks in the sport or recreation of their choice have thereby been reduced (Reilly & Lees, 1984).

Training routines nullify their objectives if they induce trauma and consequently safety considerations are of paramount importance (Reilly & Thomas, 1978). Since most musculoskeletal injuries are caused by imbalance of internal muscle force and external environmental force, resulting damage to the anatomical biological tissues and structures, biomechanical analysis helps studying these forces and their effects and establishes injury mechanism (Viano *et al*., 1989).

2.2.7 Prevalence of resistance training injuries

The incidence of injuries during resistance training has increased over the past decade, with 25% - 30% of participants reporting an injury severe enough to seek medical attention (Powell *et al.,* 1998; Yu & Habib *et al.,* 2005). Resistance training injuries can be classified into acute and chronic injuries.

The most common acute, non-urgent resistance training injuries are muscular strains and ligamentous sprains, accounting for 46% - 60% of all acute injuries in strength training (Calhoon & Fry*,* 1999; Kerr *et al.,* 2010). There is some disagreement as to the most common injury sites. Research does indicate that there are differences in the prevalence amongst athletes participating in the various strength and power sports such as weightlifting and powerlifting. Ligament ruptures seem to be most associated with inappropriate movement of a joint. Conversely, tendon ruptures are less associated with inappropriate movement of a joint and more from overloading the tensile strength of the tendon. Tendon ruptures occur more frequently in those using certain muscle-enhancing products, those recently having used fluroquinoloanes, or those over the age of 40 (Lavallee & Balam, 2010).

Acute injuries can be subcategorized into non- emergent and emergent types. Emergent injuries include acute herniated discs, fractures, dislocations, myocardial infarction and spontaneous pneumothorax. These often require discontinuation of the training and transfer to a medical facility. Non-emergent acute injuries such as small lacerations or mild strains usually only result in a brief respite from lifting (Calhoon & Fry, 1999; Lavallee & Balam, 2010).

Chronic type injuries tend to be as a result of overuse or incorrect training technique or form and account for approximately 30% of injuries associated with resistance training (Calhoon & Fry, 1999; Raske & Norlin, 2002). Tendinopathies are the most common chronic injury to be encountered. Other common chronic injuries include arthritis of the major joints related to repeated stresses placed upon those joints during training and competition over years or even decades of performing the same motion. More severe chronic type injuries include stress fractures. In resistance training, stress fractures are not found in the long bones as seen in the running sports but located in the spine (i.e. spondylolysis) secondary to the repeated excessive loads placed on the axial spine. Any exercise with increased flexion-to-extension of the lumbar spine under load has a significant risk (Lavallee & Balam, 2010).

There appear to be variations in resistance training injuries when comparing males with females. In a study by Quatman *et al.,* (2009) it was found that women demonstrated a higher risk of accidental injuries and suffered more lower-extremity injuries compared to men. Men, however suffered more exertional-type resistance training injuries such as sprains and strains compared with women, particularly of the trunk (Figure 2.5).

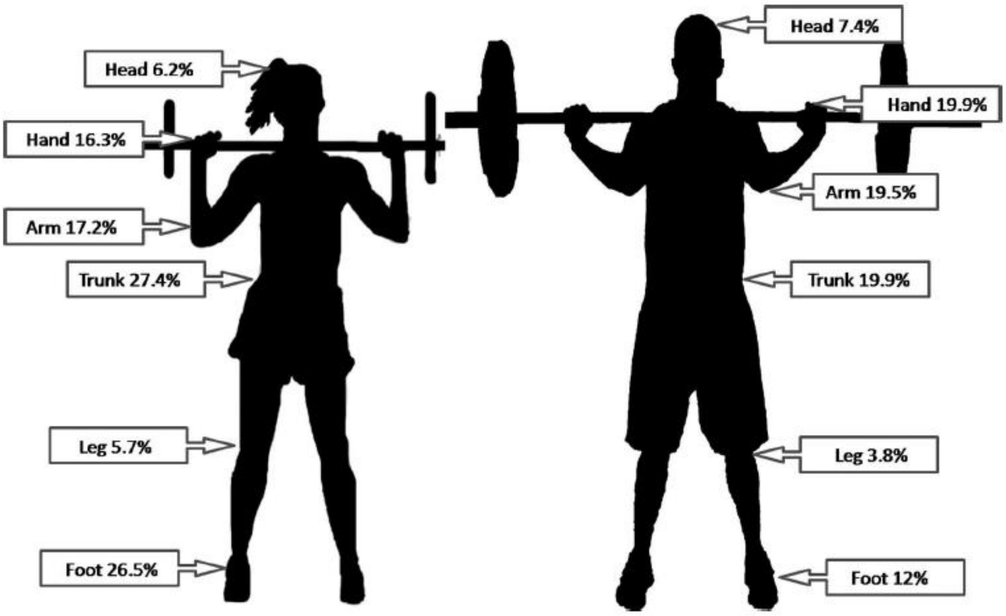

Figure 2.5: Percentage of injuries at each body location for women and men (Quatman *et al.,* 2009).

2.2.8 Resistance training equipment design evaluation

Two aspects regarding the evaluation of resistance training equipment design are discussed below, namely: 3D musculoskeletal modelling as well as the biomechanical and anthropometric analysis of resistance training equipment design.

2.2.8.1 Three dimensional musculoskeletal modelling

A computer model of the human musculoskeletal system is a mathematical description of the body in motion compiled into a computer programme. (Luttgens *et al*., 1992) (Figure 2.6). The advancement in computer technology and data processing capability has allowed the improvement of modelling software to a point where dynamic problems can now be simulated and analysed in a digital environment (Kim & Martin, 2007; Wagner *et al*., 2007; Zenk *et al*., 2005). Furthermore, computer simulations allow for the exploration of the limitations of human movement systems without endangering human subjects (Luttgens *et al*., 1992).

Mathematical and computer modelling is suitable for a wide variety of applications such as the design, production and alteration of medical equipment (prostheses, orthopaedic and orthodontic devices) as well as sports and training equipment (Alexander, 2003; Kazlauskiené, 2006). With the capability to simulate musculoskeletal human models interacting with mechanical systems many questions concerning the effects of the resistance training equipment on the body can be studied. In addition, computer simulation models permit the study of the complex interactions between biomechanical variables (Kenny *et al*., 2005).

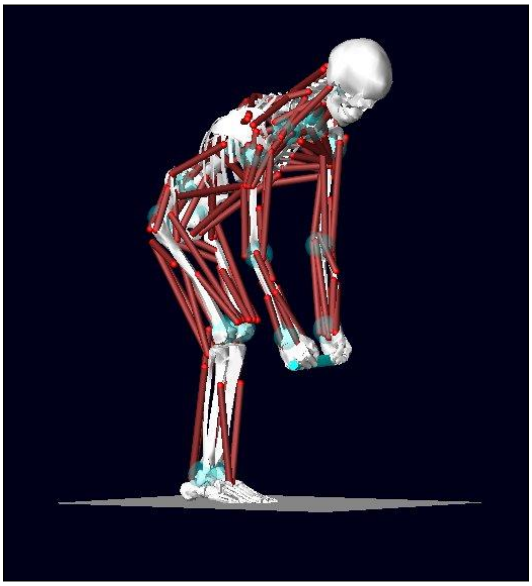

Figure 2.6: Example of LifeModeler^{TM} musculoskeletal human model.

There are two approaches to studying the biomechanics of human movement: inverse dynamics and forward dynamics. The aim of such models is to estimate or predict muscle forces, joint moments and/or joint kinematics (Buchanan *et al*., 2004). The most widely used digital human modelling software systems, such as Jack and Safework, lack built-in inverse-dynamics capability. However, newer software systems such as LifeModeler^{TM}, AnyBody, SIMM and OpenSIMM are making these computations available for ergonomics applications (Wagner *et al.*, 2007). LifeModeler^{TM} and AnyBody software have been used on various research projects in the field of sport, exercise and medicine (Schillings *et al*., 1996; Rietdyk & Patla, 1999; Hofmann *et al*., 2006; Agnesina *et al*., 2006; De Jongh, 2007; Olesen *et al*., 2009). LifeModeler^{TM} was the software of choice for this study solely due to ease of access through a current South African user which was also able to provide initial training on the software. Anecdotal evidence suggests that LifeModeler™ is currently the only software of its type being used in the South African setting.

The inverse dynamics analysis produces estimates of the joint torques required to perform a specified movement, each of which represents the resultant action of all muscles crossing the joint. Dynamic motion is then achieved (forward dynamics) via activation of the muscles, which subsequently produces force and in turn, move the joints in a controlled fashion to accomplish the pre-determined task, in this case the movement of the piece of equipment. Quite often, these tasks are also required to take place against the action of external forces such as gravity and the resistance of the weights on the exercise machine (Erdemir *et al*., 2007) (Figure 2.7).

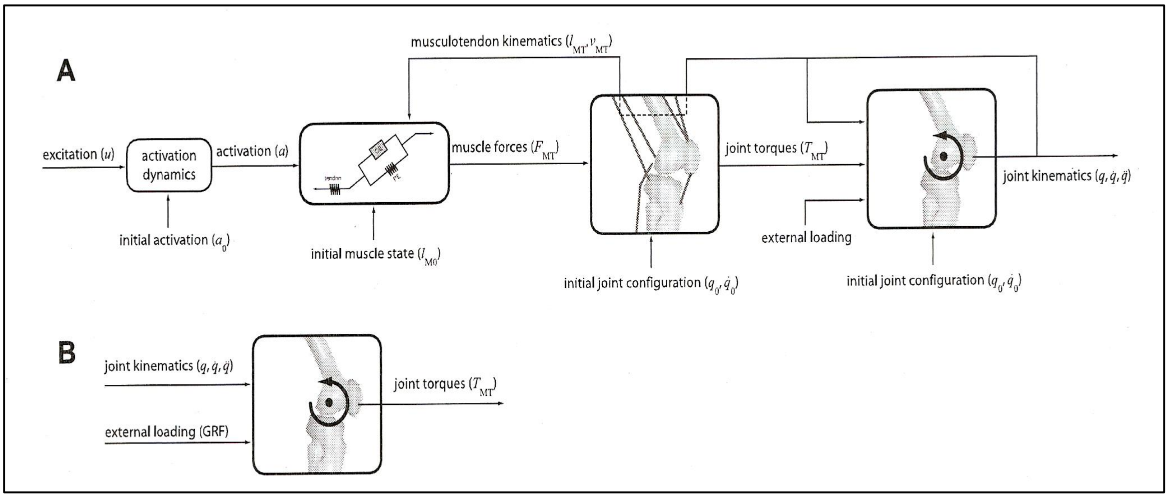

Figure 2.7: Data flow in a musculoskeletal model during forward dynamics simulations. (A) Each step, the integration scheme calculates muscle force and joint kinematics using muscle and kinematic states of the previous step. (B) Data flow in a joint torque-driven model for inverse dynamics simulations. Time history of joint kinematics and external loading are fed into linear algebraic equations to solve joint torques (Erdemir *et al*., 2007).

Data which can be obtained from LifeModeler™ following the modelling process is presented in table 2.1. LifeModeler™ contains a database of muscle tissue properties. This includes the physiological cross sectional area (pCSA) and the maximum allowable tissue stress in each muscle. Each muscle contains a contractile element in series with a spring-damper element, storing the input motion and effectively “training” the muscles to reproduce the necessary force to recreate the desired motion. The maximum force transmitted by these muscles is then determined by multiplication of the pCSA and the maximum stress.

The amount of force that can be exerted by each muscle in LifeModeler™ is calculated as follows: F_{max} = pCSA x M_{stress}, where:

- F_{max} is the maximum force that a muscle can exert;
- pCSA is the physiological cross sectional area of the muscle; and
- M_{stress} is the maximum tissue stress of the muscles (Biomechanics Research Group, 2006)

The muscle elements used during the modelling in this study are referred to as closed loop simple muscles. Closed loop muscles contain proportional-integral-differential (PID) controllers. The PID controller algorithm uses a target length-time curve to generate the muscle activation and the muscles follow this curve. Because of this approach, an inverse dynamics simulation using passive recording muscles is required prior to simulation with closed loop muscles. The closed loop algorithm is governed by the following formula: $F - P_{gain}\left(P_{error}\right) + I_{gain}\left(I_{error}\right) + d_{gain}\left(d_{error}\right)$, where:

- P_{error} is the target value – current value / range of motion
- D_{error} is the first derivative of P_{error}
- I_{error} is the time integral of P_{error} (Biomechanics Research Group, 2006).

Simple muscles fire with no constraints except for the pCSA, which designates the maximum force a muscle can exert. The graph of simple muscle activation curves will generally peak at a flat force ceiling value.

Where required models can also be driven by joints only without adding musculature to the model. This option creates a trained PID-servo type controller on the joint axis. The joint is commanded to track an angular history spline with a user-specified gain on the error between the actual angle and the commanded error. A user-specified derivative gain is specified to control the derivative of the error.

The LifeModeler^{TM} default model has a full body set of 118 muscle elements attached to the bones at anatomical landmarks, which includes most of the major muscle groups in the body (Table 2.2) (Biomechanics research group, 2006).

Table 2.1 : Data which can be obtained from LifeModeler™ following the modelling process (Biomechanics Research Group, 2006).

Body motion data for each body segment (kinematics)	Position Velocity* Acceleration** Angular acceleration**
Soft tissue data (kinematics)	All muscle force and contraction histories
Joint data (sagittal, transverse and frontal planes)	Torque*** Angle
Contact forces	Contact forces

*Velocity: Linear velocity is the rate at which an object changes its position, it includes the direction and describes the rate of displacement (Floyd, 2009). While angular velocity is the rate of rotary displacement (Hamilton *et al.,* 2009).

**Acceleration: Linear and angular acceleration may be defined at the rate of change of velocity (Floyd, 2009; Hamilton *et al.,* 2009).

***Torque: Torque or moment of force, is the turning effect of an eccentric force (Floyd, 2009).

Table 2.2 : LifeModeler^{TM} default model muscles (Biomechanics Research Group, 2006). Note that the values in brackets indicate that a muscle might have more than a single element presenting either different heads or fibre orientation.

- Scalenus anterior
- Scalenus medius
- Scalenus posterior
- Splenius cervicis
- Splenius capitis
- Sternocleidomastoid
- Rectus abdominis
- Obliques
- Erector Spinae (1-3)
- Pectoralis major (1-5)
- Pectoralis minor (1-3)
- Iliacus
- Iliopsoas
- Gluteus maximus (1-2)
- Gluteus medius (1-2)
- Rectus femoris
- Vastus medialis
- Vastus lateralis
- Biceps femoris (1-2)
- Semitendinosis
- Adductor magnus
- Gastrocnemius (1-2)
- Soleus
- Tibialis anterior
- Psoas major (1-5)
- Psoas minor (1-3)
- Trapezius (1-4)
- Subclavius
- Latissimus dorsi (1-3)
- Deltoid (1-3)
- Biceps brachii (1-2)
- Brachialis
- Triceps brachii (1-3)
- Pronator teres
- Flexor carpi (1-2)
- Flexor pollicis
- Flexor digitorum
- Extensor carpi
- Extensor digitorum
- Abductor pollicis

2.2.8.2 Biomechanical and anthropometric analysis of resistance training equipment design

Anthropometry is the science of measurement and the art of application that establishes the physical geometry, mass properties and strength capabilities of the human body. The name derives from anthropos, meaning human, and metrikos, meaning of or pertaining to measuring (Roebuck, 1993).

When exercising, people may adopt unhealthy postures that put strain on their musculoskeletal system especially when they are adopted for extended periods of time. The cause of exercisers adopting unhealthy postures may be the result of a number of factors, namely:

- The design of the exercise equipment. Limitations in the equipment design that does not allow adjustability to accommodate the appropriate range of anthropometric variances;
- Limited knowledge regarding correct exercise technique and/or posture;
- Fatigue; and
- Overloading i.e. trying to lift excessive resistance.

When designing equipment to promote appropriate exercise posture, anthropometric data should be considered a key resource. It is important that exercise equipment accommodates a range of anthropometric dimensions that is suited to the population group (end-user population) that will make use of the equipment.

Other factors can also be assessed to determine musculoskeletal injury risk such as maximal muscle tensions. Muscle tensions near or higher than maximum calculated capacity or above realistic measurements for the muscle group could indicate risk for musculoskeletal injuries. It is also possible to compare safe-loading limits of joints with recorded values during the 3D musculoskeletal modelling. The limitation of this approach is that limited safe-loading joint limit values are available and the most readily available are those for the spine. The vulnerable joints during a particular exercise vary according to the requirements of the movement and the joints involved in the movement however in most exercises the spinal column remains a commonly injured area (acute or chronic) of the body and therefore it is useful to assess these values (Calhoon & Fry, 1999; Lavallee & Balam, 2010).

Both anthropometry and muscle force production could be used in assessing exercise efficacy. Force exertion in any movement will involve many muscles, some acting as prime movers in generating force and others acting to stabilise the joints in the rest of the body. Force is exerted through the body like a “kinetic chain”. Thus, the limiting factor in the maximum force that can be exerted is most likely to be determined by the weakest link (the most highly stressed muscle). When a person is forced to adopt an awkward posture for exertion, it is likely that some of the muscles in the kinetic chain will be attempting to exert torque under less than optimal conditions with either muscle length or movement arm sub-optimal thereby decreasing the efficacy of the exercise and possibly increasing the risk of injury as well (Delleman *et al*., 2004).

With the complexity of such kinetic chains, it is obvious that there will be wide individual variations in strength and risk of injury due to anatomical variability, differences in anthropometric dimensions and differences in physiological condition (muscle fibre composition, strength and fitness) (Delleman *et al*., 2004). Nevertheless, common principles can be established for postural strategies that can assist in allowing an individual to exert maximum force when performing a particular exercise and lowest risk to injury. These principles can be used in forming guidelines for the design of exercise equipment as high forces will be exerted.

2.3 CONCLUSION

The popularity of training and exercise, specifically resistance training has increased dramatically over the last few years. Unfortunately it does not appear as if most pieces of exercise equipment undergo any vigorous scientific evaluation focusing on the anthropometric and biomechanical considerations of the end-user. 3D musculoskeletal modelling may be a practical way of evaluating resistance training equipment thus decreasing the risk of injury and maximising the efficacy of the exercise for the exerciser.

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