ANTHROPOMETRIC MODELLING OF THE HUMAN VERTICAL JUMP

by

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ANTHROPOMETRIC MODELLING

OF THE HUMAN VERTICAL JUMP

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Abstract

This research investigated the statistical relationships between human macro structure, as measured by anthropometry, and a generic motor performance, the standing vertical jump. One hundred subjects (68 males and 32 females, comprising 59 athletes in various sports and 41 Kinesiology students) underwent 42 standard anthropometric measurements. Additional derived variables quantified shape, proportion, and composition. Two new lower extremity shape indices were designed: an *angularity index* for the thigh and shank segments, and a *proximorphy index* (to quantify the extent to which the lower extremity muscle mass was centred near the trunk, as is found among the best animal jumpers).

The subjects performed nine vertical jumps on a Kistler force platform, separated by 1 minute recoveries. This included three random-ordered trials for each of three types of jumps: a *static jump* (SJ) from a squat position, a *counter movement jump* (CJ) (both of these with hands remaining fixed on hips) and a *reach jump* (RJ)(with arms swinging upwards).

An anthropometric analogue of an explanatory physics equation provided a theoretical framework for the modelling. After principal components analyses for data reduction, forced multiple regressions determined the final unisex models, which included $\log_{(\text{base } 10)}$ mass adjusted sum of eight skinfolds and the proximorphy index as the best paired significant explanatory variables, together accounting for 35% to 50% of the jump height variance. When tested on 68 male professional hockey players, the models actually performed better than on the sample upon which they were based. The proportion of the variability (multiple r) explained by structure was 0.57 - 0.70, and this was statistically significant ($p<0.001$). Major non-structural causative factors are likely to preclude more precise prediction.

Significant ($p < 0.001$) correlations were found between peak forces in the jumps and certain structural variables (skinfold-adjusted mid-thigh girth^2, $r = 0.78 - 0.85$; proximorphy index, $r = 0.53 - 0.60$). The peak forces themselves correlated rather poorly ($r = 0.39 - 0.54$) with the height of those jumps. It appears that a physiological component of this skill may be easier to predict from anthropometry than the skill itself.

Dedication

To Dr. Bill Ross, who, even upon his "retirement" from a distinguished university career this year, continues to view science with the awe and enthusiasm of an eager child. Merely by association, his students cannot help but learn that a passion for history need never stand in the way of new ideas. Indeed, it encourages them.

And to Jake, a dog and friend, who always reminded me of my roots.

Quotations

"All animals, provided always they are similarly fashioned, with their various levers in like proportion, ought to jump not to the same relative height but to the same actual height."

(D. W. Thompson, 1942)

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Chapter I

INTRODUCTION

The study of the effects of size and scale in the world is an ancient subject. Archimedes (287-212 BC) was perhaps the first to elucidate the mathematical relationship which links similarly shaped, solid geometric structures of different sizes, to see the concept of the ratio applied to geometric forms, and to describe how surface area increases as the square of the linear dimensions while volume increases as the cube (see Thompson, 1917). Galileo Galilei (1564-1642) expanded this understanding to encompass the strength of materials, showing (assuming constancy of shape and composition) that if a structure increased in all dimensions equally, its weight would increase as a cubic function (proportional to volume) while its strength would increase only by a square function (proportional to cross-sectional area). He thus provided us with the theoretical explanation of what is now known as the *cube-square law*; i.e. the fact that, if shape and composition are constant, volume (and mass) increase as the cube of linear dimensions but strength increases only as the square (see Ross et al., 1980). His student, Giovanni Alphonso Borelli (1608-1679), extended these concepts to a mechanical analysis of the muscular action involved in animal locomotion, in his book *"De Motu Animalium"* (Concerning Animal Motion), and noted that strength has a dimension of $[L^2]$, which is related to the cross-sectional area of muscle (see Ross et al., 1980). Borelli also noted that the velocity of running is a function of leg length $[L^1]$and stride frequency $[L^{-1}]$ and therefore is dimensionless ($[L^1] X [L^{-1}] = [L^0]$); in other words, running velocity is theoretically independent of size, when shape is held constant. He also noted that geometrically similar animals jump to approximately the same height (Ross et al., 1984, p. 79). Further, Bennet-Clark notes:

> "if all animals have the same proportion of muscle capable of producing the same specific energy, they should all jump to the same height".
> (Bennet-Clark, 1977, p. 187)

Ever since then there have been periodic attempts by scientists in all fields to understand and describe the relationships between structure and function, size and performance. The great advances were made first by physicists and engineers, primarily during the Industrial Revolution (see McMahon and Bonner, 1983), during which time it became of great practical importance to understand how the weight, strength, power and other physical properties of structures changed with size, in order to design safe buildings and bridges, efficient motors, etc.. But biologists eventually became interested, and areas within biology began to formalise the links in living organisms between size and proportions (e.g. Thompson, 1917), size and growth (e.g. Huxley, 1932 and Tessier, 1931), size and physiology (e.g. Kleiber, 1932), and size and locomotion (e.g. Gray, 1936; Alexander, 1968, 1971, 1974; Bennet-Clark, 1977).

While builders, engineers and physicists have long understood the limitations which size places on function, it was not until the 1830's that a French physiologist (J.F. Rameaux) and a mathematician (P.F. Sarrus) formalised this understanding in biology (see McMahon and Bonner, 1983, p.xi), when they realized that an animal loses heat through the surface of its body (i.e. area) while its capacity for heat production was related to its muscle mass (i.e. volume). This simple dimensional analysis explains why the larger the animal, the greater its capacity for heat production relative to its capacity for heat loss. (It should be noted that heat production via metabolic rates has since been found within individual species to be proportional to mass$^{0.67}$ (i.e. area), but across species to follow Kleiber's Rule of being proportional to mass$^{0.75}$ - known as the equation for the *'mouse to elephant curve'* (see McMahon and Bonner, 1983, p.64-66, Calder, 1984, p. 28-29, Ross et al., 1984, p. 81-83). This dimensional relationship is also the basis for Bergmann's Rule; i.e. the tendency towards size increase in cooler temperature zones versus equatorial areas.)

It began to become clear to biologists that

> "there are certain shapes that are physically impossible for large organisms, and there are others that are equally impossible for small ones."
> (McMahon and Bonner, 1983, p. 18).

In areas of human physical performance, particularly in sports, size is generally acknowledged to be one of the determinants of function. It is desirable for basketball and volleyball players to be tall, for endurance runners to be light, and for football linemen to be heavy. In some sports, size is acknowledged as being so important as to warrant the segregation of athletes into size-dependent categories. We have long been accustomed to seeing weight classes in boxing, wrestling and weight lifting, etc.. Recently, height was used as a segregating criterion, when a professional basketball league was established for players under 6 feet 5 inches in stature.

At a slightly more subtle level of understanding, there has been recognition of a duality with respect to *weight-bearing* activities (e.g. running), in which performances are limited by the weight of the athlete, and *weight-supported* activities (e.g. cycling), in which they are much less affected by the athlete's weight (except when going up hills, of course!).

Similarly, a distinction is sometimes made between sports in which *absolute strength* is important (as when force is exerted against another athlete's mass or the standard mass of an implement), and sports in which *relative strength* is required (i.e. relative to the athlete's size, as when force is required to accelerate the athlete's own mass, thereby demanding high *force mass ratios*). Examples of the former would be football and shot putting, while the latter would be shown by gymnastics and swimming. Tittel (1978) has suggested that the former type be termed *centrifugal* activities (where movements are directed away from the athlete's centre of mass via the extremities toward an external resistance), while the latter be called *centripetal* activities (where movements are directed from the extremities toward the athlete's centre of mass). Some biomechanists, however, may not feel comfortable with this classification.

While size is usually acknowledged to be important in human physical performance, the relationship is sometimes oversimplified and taken too much for granted. For example, the tremendous muscularity of Canada's infamous sprinter, Ben Johnson, is usually credited as being the direct source of his world-record performances, and as being indicative of his ability to generate large forces against tne ground. However, an overly simplistic application of the principles of dimensional analysis might suggest that the increase in his muscularity could actually hurt him, since strength and power are at face value related to the cross-sectional area of muscle mass (i.e. a square function) while weight is related to mass and volume (i.e. a cubic function). One could theorize that while he becomes stronger with increases in muscle mass, his increases in weight would appear to be greater than his increases in strength. Since we know from Newtonian physics that

$$ACCELERATION = FORCE/MASS \qquad \text{(Eq.1)}$$

it follows that if an athlete's weight (i.e. mass) increases more than his strength (i.e. force), acceleration should be impaired.

Since Ben Johnson's career changes in muscle mass appeared to be positively correlated with the changes in his ability to accelerate (it is generally accepted by coaches and athletes that this relationship can be found in most sprinters, within reasonable limits) other factors must be at work to provide departure from this simple dimensional analysis.

In fact, this analysis is based upon a geometric similarity model, which assumes that Johnson does not change shape or proportion when he puts on muscle mass. Of course, he does! Furthermore, the geometric similarity model makes assumptions of constant densities and functions which are not true in a complex structure such as a human being. Univariate relationships, such as those implied by the geometric similarity model, are usually inadequate to describe biological phenomena. However, they may sometimes provide a worthwhile starting point from which departures can be analysed. This topic is discussed further in chapter II, under departure models.

An elementary analysis of competitive weight lifters, however, shows that for them, the geometric similarity model does provide an excellent description, and therefore prediction, of performance (Lietzke, 1956). The total weight lifted in three Olympic events (the press, the snatch, and the clean-and-jerk) generally increases with the weight of the lifter. While the heavier weight classes obviously have the greater world records in terms of absolute amounts of weight lifted, if the lift records are divided by the weights of the lifters themselves, it can be seen that the greatest power/weight ratios come from the lightest weight classes (Lietzke, 1956). Pound for pound, kilo for kilo, the most powerful athletes are generally the smallest ones. In a sense this shouldn't surprise us, since the field of biology gives us many examples of this. Went (1968) has pointed out that an ant can lift ten times its own weight, while we know that a human will generally be limited (depending upon the specific lift used) to less than three times body weight.

In providing a dimensional analysis of world-record weight lifters, Lietzke (1956) showed that the total weight lifted in all the body-weight classes up to 198 pounds is almost exactly proportional to the 0.67 power of body weight. Ross et al. (1978) found similar results among the champion weight lifters in thirteen Olympiads from 1920 to 1976. These findings are perfectly in accordance with an isometric model (i.e. geometric similarity across size differences, with strength increasing as a square function in relation to weight increasing as a cubic one). It also suggests that the muscle weight/total weight proportions of the world-record and Olympic champion weight lifters are the same in each body-weight class. In other words, world-record and Olympic champion weight lifters fit an isometric model to a high degree, and have very similar structures scaled proportionally to body weight. Further, the close fit of the real data to this isometric model allows us to predict, with reasonable accuracy, world record and Olympic championship weight lifting performances based on one aspect of structure (i.e. weight lifted is proportional to body weight to the 0.67 power).

There are many areas of physical activity, though, where attention to the role that structure plays in performance is inadequate or even non-existent. Physical fitness tests, which are really physical performance tests, typically reference raw score results to norms based on age and sex. Seldom are any structural parameters considered (see Montoye et al., 1972). For example, sub-maximal step tests are often used to evaluate cardiorespiratory fitness, and the heart rate measures during or immediately after these tests are compared with age and sex norms to provide ratings of cardiorespiratory fitness.

It is obvious, however, that structure can potentially play a major factor in this performance. Since bench-stepping is a weight-bearing activity, one might expect a heavier person to perform more poorly (i.e. have higher heart rates) than a lighter person, even when they have cardiorespiratory systems with identical capacities. Similarly, the heavier person may show considerable improvements in test scores (lower heart rates) simply as a result of losing weight (having less mechanical work to do), and without necessarily having any improvement occur within the cardiorespiratory system.

Age and sex norms may, in fact, give misleading impressions. Are sex differences in strength, for instance, best described as being due to the sex of the individual, or could they be better explained by the differences in structure which usually relate to a person's gender? As is so often the case, there may not be a simple answer.

The well-known study by Ikai and Fukunaga (1968) showed that the strength per unit cross-sectional area of the biceps brachii in forearm flexion at the elbow, had fairly constant values in male and female, young and old, and trained and untrained individuals. Similarly, it has been shown that muscular strength increases in a similar manner in response to weight training in both males and females (Lewis et al., 1986; Gettman et al., 1982). Females have been shown to achieve greater initial strength gains, but this has been attributed to their lower strength levels prior to training (Gettman et al., 1982; Hakkinen, 1985; Wilmore et al., 1978). Some studies have suggested that females develop less muscle hypertrophy than males as a result of weight training, and it has been suggested that this is because of the reduced female testosterone levels. However, these studies have often used only indirect measurements of muscularity, based solely on changes in lean body mass (e.g. Brown and Wilmore, 1974; Mathews and Fox, 1976).

Bell and Jacobs (1990) performed muscle biopsies on male and female body builders and controls, and found that while the female body builders' slow twitch fibres had hypertrophied to a similar extent as the male body builders', the male body builders' fast twitch fibres had hypertrophied more than the female ones. This possibly selective hypertrophy of the fast twitch fibres may be a sex-related factor in strength performance, perhaps responsive to varying testosterone levels. When strength was expressed per kilogram of body weight, the body builders of both sexes were stronger than the controls, but the gender difference disappeared.

Similarly, performance decrements which often result from increasing age may be concomitant with structural changes due partly to the aging process, and partly to the lifestyle changes that tend to occur with age. With the current trend towards aging being accompanied by the maintenance of active lifestyles, age norms for both structure and performances may soon improve considerably over those that exist now. One might suggest that age (and the aging process) is less worthy of being entitled to a normative classification for performance than are measures of size and structure.

Two prominent and well-documented systems for quantifying body structure are the Heath-Carter Somatotype (Carter, 1975) and the Phantom Proportionality Profile (Ross and Wilson, 1974). Both of these systems are size-independent, in that the resultant shape and proportionality characteristics can theoretically be found at any height or weight. The Ross-Wilson proportionality profile uses a unisex phantom as an arbitrary model, such that when an individual's anthropometric values are dimensionally scaled to a phantom value (usually height, set at 170.18 cm. for the phantom) these values can then be expressed as deviation scores from the phantom model. It is worth noting that experts in these systems of structural description can very often identify what sport an elite athlete is engaged in by simply looking at his or her structural characteristics as defined by these systems. Carter (1981), Ross and Ward (1984), and DeRose et al. (1989) have measured and described the structures of Olympic and other elite athletes in published studies using these techniques.

So if structure plays such a predictable role in the success of elite athletes in so many sports, each of which is normally comprised of a number of different skill performances, it seems reasonable to assume that structure may play an even greater role in the performance of many more specific skills and movements. Further, it appears reasonable to suggest that more detailed descriptions of the relevant force-producing body segments may provide even better predictions of a given performance. And if the predictions of performance are improved, perhaps these structural concomitants will lead to a better understanding of some of the factors involved in creating those performances. The primary purpose of this research was to examine these questions with respect to the human performance of a standing vertical jump.

PURPOSES

The general purpose of this research was to investigate the relationships between structure and function - specifically, between human external macroscopic morphology and a particular human physical performance. This involved studying the anthropometric concomitants of three types of a relatively simple, commonly performed physical skill (i.e. the standing vertical jump), in order to:

1. determine the extent to which the variability in performances can be explained by the variability in structures;

2. develop theoretically-based mathematical models to predict the jump performances, from an anthropometric analogue to an appropriate explanatory physics equation , and;

3. test the developed models on a sample different from that upon which they were based.

The standing vertical jump was chosen as the performance for the following reasons:

1. it is a relatively simple skill derived from a fundamental movement pattern with which almost everyone has some experience, and it may therefore be considered *"phylogenetic"* , as opposed to *"ontogenetic"* or culturally acquired (see Newell, 1986 and Van Wieringen, 1986). This also enables broad comparisons across animal classes, since jumping is a fundamental part of animal behaviour;

2. the relatively minimal requirements for co-ordination diminish the effect of learning on the performance;

3. its short time span eliminates the energy systems as a limiting factor, and reduces the drain on motivation over repeated trials;

4. the discreteness of the skill simplifies its analysis;

5. it is a convenient performance to measure, either in field situations (with many existing test protocols) or in the laboratory (with force platforms, cinematography, and timing mats).

The following general approach was taken:

1. Techniques were devised for describing the shape of body extremities and segments, particularly with respect to some of the underlying force-producing structures which were likely to be important in jumping.
2. Existing research on the biomechanics and physiology of jumping was reviewed, with regards to the development of specific jumping techniques which attempted to control some of the sources of biomechanical and physiological variability.
3. One hundred sixty-eight subjects were measured using comprehensive anthropometry (including the new segment shape techniques). Three repetitions of three different types of vertical jumps were then performed, according to a randomly assigned order.
4. Theoretically-based and statistically-derived models, constructed from the anthropometric variables of ninety-one of the subjects, were produced to predict vertical jumps from surface anthropometry. The theoretical modelling began by looking at the physics of vertical jumping, and by choosing a physics equation that would best lend itself to developing an anthropometric analogue. Relationships between size and jumping ability, both across animal species and within *homo sapiens*, were then investigated, in order to define candidate variables for the anthropometric analogue. These variables were confirmed on the collected data by principal components analyses and correlation matrices. Forced multiple regressions determined the final models, which were then tested on a sample (n = 68) different from that upon which they were derived.

RELEVANCE

1. To add to the general body of knowledge concerning the structural basis of human performance, and to further define the limitations which size and shape place on human physical capacities.

2. To add to the understanding of how standing vertical jump performances may be related to human shape and structural characteristics.

3. To contribute, to the specialisation of kinanthropometry, validated techniques for the description of the shape and structural characteristics of body segments.

4. To provide a mathematical model for predicting vertical jump performances based on structural criteria, thus enabling performance expectations and predictions for individuals.

Chapter II

REVIEW OF THE LITERATURE

The following review of the literature is divided into two major sections. The first section, on structure, provides a philosophical perspective on the relationship between structure and function, especially as delimited by kinanthropometry. The concepts of dimensionality and allometry are discussed as requisites to the understanding of how size relates to physical performance. The need for departure models is addressed, and the Ross-Wilson (1974) *phantom* is described as a vehicle for quantifying departures from theoretical, dimensionally scaled expectancies. Suggestions are made as to how this approach may provide a basis for expansion to include the quantification of more detailed size and shape characteristics of individual body segments, particularly those segments that provide the major forces required in vertical jumping.

Section two begins with an overview of the basic principles of the mechanics of jumping; principles which are based in Newtonian physics and which apply to all forms of life. Jumping is explained as a fundamental part of animal behaviour, and the literature relating to jumping across the animal species is examined. The possibilities for allometric relationships are discussed in three contexts - cross-sectionally, (1) across a range of animal species, (2) across the human species; and longitudinally, (3) reflecting growth, training and aging within individual humans. Research on human vertical jumping is reviewed, with regard to both laboratory and field tests, and demonstrated relationships among various anthropometric descriptions of size and jumping ability are summarized. Some theoretical relationships for investigation are proposed. Finally, statements are made regarding the biomechanical, physiological and other factors which may affect vertical jump performance and provide non-structural sources of variability.

Section 1 - STRUCTURE

The Quantification of Structure:

The notion that structure and function are inextricably linked has intuitive appeal, and if we take a reductionist view of life, we could argue that all function at a sub-cellular level involves a change in structure - if nothing more than the transformation of one molecule into a different one in order to provide for a release in energy. As we increase our perspective macroscopically, however, the linkage becomes more difficult to define. Molecules are relatively simple and predictable in their behaviour, but as we zoom out through cells, tissues, organs, systems and whole organisms, the increasing complexity of the structures makes the prediction of their functions and capacities much more indefinite. Biological constants which may exist at the biochemical and even cellular levels become biological variables with probability distributions at the macro level.

So when we search for a relationship between structure and function at the level of a complex organism such as *homo sapiens* (e.g. in order to predict human vertical jump heights from structural parameters) we must acknowledge from the outset that structure (at least as kinanthropometrists can measure it) is likely to account for only a certain proportion of the variability in the function. Many other variables are likely to be involved - some of which may have no structural correlates (e.g. thought processes, motivation, attention, learning, skill and segmental timing - although there may even be a structural basis to these!) and some which do represent known structures but which fall within the domain of another discipline such as physiology (e.g. proportion of fast twitch muscle fibres in a given muscle, accumulation of fatigue-related products, etc.).

Ross et al. (1982a) describe *kinanthropometry* as involving the quantitative interface between anatomy and performance (structure and function). It involves the measurement of size, shape, proportion, composition, and maturation (the perspectives of structure) for linkage with measurements of gross function. While human structure is so varied as to provide an infinite number of potential relationships between the innumerable structural variables and the performance in question, scientific wisdom based on existing theory must single out those relationships most worthy of investigation. The process of statistically modelling the human vertical jump based on the morphology of individuals must begin by searching for explanatory relationships.

Dimensionality:

Buildings, dams, machinery, ships and jumbo-jet airliners are (fortunately) no longer built on a trial and error basis. Using scaled down models, prototypes can be built and tested until confidence permits the full-scale version to be constructed. For example, scale models of skyscrapers may be built in order to test resistance to twisting and swaying in high winds. It becomes extremely important, then, that every aspect of the building is scaled proportionately, in a way that makes dimensional sense.

Biologists sometimes use scaled up models to allow small structures and functions (for example, capillary blood flow) to be analyzed at a more convenient size. In general, as McMahon and Bonner (1983) state:

> "In dimensional analysis, the object is to substitute a set of dimensionless numbers for the dimensional physical variables that describe a problem - pressure, velocity, density, and so on. Because the dimensionless numbers are products or ratios of the physical variables, this process always succeeds in reducing the number of variables in a problem."
>
> (McMahon and Bonner, 1983, p. 71).

Physical variables always require instruments for their measurement (e.g. a scale for weight, a tape measure for girth, a clock for time). The minimum number of basic instruments needed to measure a physical variable can thus define the fundamental quantities for that variable (i.e. its dimensional formula). Dimensional formulae are denoted by capital letters raised to appropriate powers and enclosed in square brackets.

Three of the more commonly used dimensional systems are shown in Table 2.1 below. The *'mass-length-time'* [MLT] system and the completely equivalent *'force-length-time'* [FLT] system are shown in columns 2 and 3 respectively. Ultimate simplicity is achieved when the primary Newtonian quantities of mass, force, length and time are all reduced to a power of a single quantity [L], as is shown in the *'physiological'* system in column 4, by making 3 assumptions (see Asmussen, 1973; Ross et al., 1984, p. 79):

1. mass is proportional to volume (i.e. $[L^3]$);
2. force is proportional to area (i.e. $[L^2]$);
3. time is proportional to length (i.e. $[L^1]$).

Thus, any parameter that can be defined in the MLT or FLT systems can be expressed in dimensions of [L]. And, "any size-dependent performance can be ascribed a theoretical expectancy" (Ross et al. 1984, p. 79).

Parameter	MLT	FLT	Physiological
Length, l	[L]	[L]	[L]
Time, t	[T]	[T]	[L]
Force, F	$[MLT^{-2}]$	[F]	$[L^2]$
Area, A	$[L^2]$	$[L^2]$	$[L^2]$
Frequency, f	$[T^{-1}]$	$[T^{-1}]$	$[L^{-1}]$
Mass, m	[M]	$[FL^{-1}T^2]$	$[L^3]$
Velocity, v	$[LT^{-1}]$	$[LT^{-1}]$	$[L^0]$
Acceleration, g	$[LT^{-2}]$	$[LT^{-2}]$	$[L^{-1}]$
Pressure, P	$[ML^{-1}T^{-2}]$	$[FL^{-2}]$	$[L^0]$
Energy, (Work), E	$[ML^2T^{-2}]$	[FL]	$[L^3]$

Table 2.1 - Dimensional Formulae (Modified from McMahon and Bonner, 1983, p. 75 and Ross et al., 1984, p. 89).

With these dimensional formulae as tools, the physical construction of scaled models is not always necessary. In the case of mathematical models (for instance, in predicting vertical jump from structure) any theoretically derived equation can quickly be checked for dimensional consistency before being assessed empirically

Allometry:

William A. Calder III, in his landmark review "Size, Function, and Life History" (1984), describes allometry as the "quantitative representations of the consequences of size" (p.ix). He then states that one of his purposes in using allometry is "to separate the background biology of size from that of other variables, so that these variables can be studied in their own right" (p.ix). In light of his assertion that "any biological study must first consider size as the most significant characteristic of an animal" (p. ix), allometry is used in this research as a framework to provide insight to what is currently known about the structural predictors of vertical jumping. The ultimate objective is to separate size (and shape) predictors in order to see what variability in performance may be left to non-structural variables.

While allometry is essentially an empirical study of correlations, and correlations do not provide us with proof of causation, nonetheless important relationships can be established from which experiments to show causation may ultimately be stimulated. In other words, allometry can provide a "basis for speculation that may form bridges between artificial subdisciplines and produce a more coherent view of biology" (Calder, 1984, p.x).

In zoology, *"isometry"* (i.e. of the same measures) exists more as a conceptual base; a theoretical point of departure. "Mammals are similar to one another more than they are different" (Calder, 1984, p. 28). However, thousands of species provide "the million-fold range in body weight found in terrestrial vertebrates" (Taylor, 1977). And these many species may be viewed as being dimensionally and functionally similar except for evolved adaptations required by their differences in size. Calder states that "the differences among species are largely due to size differences" (1984, p. 28), and that size accounts for about 75% of the variability among species. Presumeably, if size can be held constant, the remaining 25% of the variability may be analyzed for size-independent factors.

For instance, if we isometrically scaled a mouse to be the size of an elephant, its height would increase in one dimension [L^1], whereas its strength would be proportional to its muscle cross-sectional area [L^2] and its weight proportional to its volume [L^3]. This new elephant-sized mouse would not be able to stand on its own own legs, since its weight would have increased much faster than its strength. And if it had a metabolic rate as quick as that of a mouse, it would overheat and cook itself to death, since its metabolism would have increased by an exponent of about .73 body mass (Kleiber, 1961) while its ability to dissipate metabolic heat production through the surface area of the skin would have increased only by an exponent of approximately .67 body mass. In other words, life forms cannot evolve to be substantially larger isometrically, and dimensional and functional differences among species have become necessary in order to allow them to become the sizes they are as a result of being naturally selected by their environments. Thus allometry (i.e. of different measures) is the study of differential growth, in which one variable grows at a different rate from another or from a given model. It is inevitable in describing size changes and it is really the study of the "differences in proportions (in structure and function) ... correlated with changes in absolute magnitude of the total organism or of the specific parts under consideration... the study of size and its consequences" (Gould, 1966).

> "Although comparisons between species often show a regular change in shape with increasing size, comparisons among different-sized individuals of the same species generally reveal a reasonably faithful isometry."
> (McMahon and Bonner, 1983, p. 51)

The relationship between biological variables and size can be described by the allometric equation devised by J. S. Huxley (1932) with important contributions by Georges Tessier (1931) (see McMahon and Bonner, 1983, p. 25; Calder, 1984, p. 28).

$$Y = aM^b$$

(Eq. 2)

(Calder, 1984, p. 26)

where:

Y = a structural, physiological or performance variable correlated with size;
M = the scaling variable representing size, usually taken as mass in kg. Height may be used instead to scale, especially when using allometry within the human species, since it is less influenced by nutrition and exercise (Ross et al., 1984, p. 80);
b = the exponent (or slope in the logarithmic version below) which acts as a scaling factor describing the effect of a change in size M on the variable Y;
a = the coefficient (or Y intercept in the logarithmic version below) which estimates the limit of Y as M approaches 0.

Since curvilinear relationships are often produced with this equation (when $b \neq 1$), it is frequently better to use the logarithmic transformation, which takes the form of a straight line in the log Y - log M plane:

$$\log Y = \log a + b \log M$$

(Eq. 3)

(Calder, 1984, p. 26).

The coefficient a normally bears the burden of carrying all the dimensions necessary for dimensional consistency in the equation. However, it should be noted that, according to Riggs (1963), empirical equations based only on observations (in the absence of theory or prior knowledge of causation) can be exempted from the dimensional consistency requirement usually attached to equations, since they are not intended to express equivalence, but simply the observed correlation between two variables. The biological interpretation of the coefficient a is not altogether clear, as is discussed by Needham, 1950; White and Gould, 1965; Anderson and Busch, 1974; Ross et al., 1984.

The coefficient b is the slope of the regression line, or the rate of change in the dependent variable with respect to the independent variable. If b=0, size has no effect, since $M^0 = 1$ and Y becomes the constant coefficient a. When $b = 1$, Y increases in linear proportion to M. This is isometry. We might expect to find this relationship between stature and sitting height among, for example, adult humans of a given race. With b greater than 1, Y increases faster than M; i.e. it increases *hyperallometrically* (Calder, 1984, p. 50). Skeletons, for instance, represent an increasing proportion of body mass with increasing size of the animal. With $0 < b < 1$, Y does not increase as much as M; i.e. it increases *hypoallometrically* (Calder, 1984, p.47). For example, the brain contributes a decreasing proportion of body mass in progressively larger animals. With $b < 0$, a size increase produces a negative correlation with Y; i.e. a decrease in Y, or inverse allometry. The reduction in heart rate with increasing animal size is an example of this.

The use of allometry involves the following steps, as discussed by Calder, 1984, p. 36:

1. The raw data (independent and dependent variables) are transformed to log form.
2. Least-squares regression analysis then determines a line of best fit, with the *goodness of fit* being described by r, and the coefficient of determination (r^2) is:

$$r^2 = \frac{[\Sigma(X - \overline{X})(Y - \overline{Y})]^2}{[\Sigma(X - \overline{X})^2][\Sigma(Y - \overline{Y})^2]}$$

(Eq. 4)

(Calder, 1984, p. 39)

where:

X = the independent or predictor variable;
Y = the dependent or predicted variable.

While relationships with large coefficients of determination, i.e. approaching 1.0, are best for enabling prediction, regression where r^2 is small may still be useful if the standard deviation of predictions (S.D.$_p$) is also small. A *predictive index*, which establishes a confidence interval for the predicted variable, is given by

$$PI = (\sqrt{1 - r^2})(S.D._Y)$$

(Eq. 5)

where:

$P.I.$ = the predictive index;
r^2 = the coefficient of determination;
$S.D._y$ = the standard deviation of the Y (predicted) variable.

The least squares regression of log Y on log M is the most widely used estimate of best fit in zoology (Calder, 1984, p. 39), and it minimizes the sum of the squares of the Y-deviations from the fitted line. It yields an unbiased estimate of Y only when the independent variable (M) can be assumed to be free of errors in measurement and free of mutual dependency, along with Y, on some third variable. Linearity in the reference population is assumed.

A *major-axis analysis*, which minimizes the sum of the squares of the distances perpendicular to the fitted line, does not assume an error-free abscissa. Neither does a *reduced major-axis analysis*, which minimizes the sum of the areas of the triangles bounded by the line of best fit and lines parallel to the X- and Y- axes extending from the data points to the line of best fit. In standard units, a reduced major axis analysis is equal to a major axis analysis, since areas of the triangles are proportional to the perpendicular distances. When correlations are high, these approaches yield similar results, but differences increase when r^2 is small (see Alexander et al., 1979 and Harvey and Mace, 1982).

3. The slope (exponent *b*) and *Y* intercept (coefficient *a*) of the line describe the relationship.

A number of cautions must be considered when using allometry.

1. Calder states that "for least-squares regressions to be legitimate, variability must be fairly evenly distributed at both extremes" (1984, p.37). Raw data transformed to log form (e.g. $\log_{10}$) *may* satisfy this stipulation with certain types of data (Lasiewski and Dawson, 1969). However, the resulting variance should still be checked.
2. Log transformations can result in deceptive first impressions of minimal variance at the higher orders of magnitude (Calder, 1984, p. 37), due to the very nature of the logarithmic scale. Confidence intervals expressed in the original units may be much greater than what appear from the log transformation. Thus while allometric equations may give a good description of group means across different species, individual prediction within a species is likely to require more detailed mathematical modelling.
3. Logarithmic transformation may yield no better correlation than the simple linear regression of untransformed data (Calder, 1984, p. 37). The question then becomes practical in nature; i.e. what relationship provides the most useful approximation?

4. Particularly when used longitudinally, to study patterns of growth and development within a species (see *ontogenetically* below) a relatively poor fit may be given by a single straight line when in fact the relationship may change at a point in the animal's development. For example, in the human, arm length represents an increasing fraction of body height in the early stages of growth, but becomes an approximately constant fraction of body height in later stages (see McMahon and Bonner, 1983, p. 32-35). In fact, *b* values may appear to change throughout an entire log-log plot, suggesting either a series of straight lines with definite breaks, or a continuous non-exponential curve. In these types of cases, allometry may be of little use.
5. Data which appears to be linear over a narrow range of the independent variable may show a different form over a greater range. Exponential curves, for instance, and their linear transforms, may only be 'picked up' if the range of data is kept broad.
6. Biological allometric equations are empirically derived and their use should be restricted to the range of data upon which they are based. Extrapolation requires assumptions (see Ross et al., 1984).
7. Ultimately, allometry only describes a relationship, and does nothing by itself to explain it, other than to point the researcher in what may be the right directions.

There are at least three broad approaches in which allometry can be used in biology:

1. *Phylogenetically* - longitudinally (long-term), to provide an evolutionary perspective;
2. *Ontogenetically* - longitudinally (short-term), to provide a growth and development perspective;
3. *Statically* - cross-sectionally, as a 'snap-shot' of current relationships among a diversity of animals at comparable times, usually at adulthood.

The patterns among given variables using these three types of allometry are not necessarily the same, and the specific exponents and coefficients may differ considerably (Cheverud, 1982). Data must not, therefore, be mixed (Calder, 1984, p. 9).

Biology provides abundant allometric descriptions of structure. As animals increase in size, the ratio of the skin surface area/unit of mass decreases, since area is proportional to $[L^2]$ while mass is proportional to volume, or $[L^3]$. At the same time, the thickness of the skin increases in order to maintain its mechanical strength, but this does not make up in mass for the proportional decrease in skin area. Consequently, the skin represents a smaller proportion of body mass in larger animals (Calder, 1984, p. 15).

Since mass increases faster than stature ($[L^3]$ versus $[L^1]$), bone thickness must increase relatively more than bone length with increasing size, in order to support the greater mass of the animal. Overall, skeletal mass represents an increasing proportion of body mass in larger animals. Across mammalian species, the combined proportions of decreasing skin mass and increasing skeletal mass constitute approximately a constant fraction of total body mass, regardless of body size (Calder, 1984, p. 15).

Skeletal muscle represents a fairly constant proportion of body mass across all species; about one third to one half body mass (Calder, 1984, p. 17). Increases beyond this proportion are restricted due to the competing demands for size increases that would be made by all the organs and systems that support muscular effort - i.e. a larger heart and lungs to provide more oxygen, a bigger digestive system to provide energy-yielding substrate, and thicker and stronger bones to cope with the greater muscular forces, etc.. Furthermore, the masses of individual muscles have a quite linear, proportional relationship to total body mass (Mathieu et al., 1981). However, different species of mammals vary considerably in muscle content, from the lion at 59% of body mass (Davis, quoted in Munro, 1969) to a female domestic pig at 31% (Munro, 1969). The proportion of muscle tends to be lower in slow-climbing arboreal animals (e.g. 25-30% in sloths and howler monkeys) and higher in the quicker terrestrial runners (e.g. 45% or more in jack rabbits and greyhounds) (Ross et al., 1984, p. 86). Within a given phylogenetic class, skeletal muscle is fairly independent of body size (Calder, 1984, p. 17).

Larger mammals seem to be able to carry proportionately greater reserves of energy in the form of fat. Calder states that

> "for almost every animal dissected and weighed, a certain fraction of body mass remains unaccounted for; this fraction climbs as total body mass increases. --- A large proportion of this mass is probably body fat"
> (Calder, 1984, p. 22).

As reported in chapter one, Kleiber (1932) found that basal metabolic rates across species of mammals (the 'mouse-to-elephant curve') are proportional to mass$^{0.75}$, whereas within a species they are more closely represented by mass$^{0.67}$. While metabolic events are not the focus of this research, the potential for this type of divergence must be kept in mind when searching for structural correlates of jumping. Across species values may differ from those within species.

Departure Models:

Ross et al. (1980) state:

> "knowledge cannot spring from experience alone, but only from the comparison of intellectual inventions with observed fact."
> (Ross et al., 1980, p. 9).

Understanding cannot come solely from the accumulation of facts; it requires the development of theories which are then tested by facts. There is a danger, however, if a theory is suddenly abandoned when the facts do not fit it perfectly. The theory may be perfectly correct as far as it goes, but there may be other factors at work which introduce variability in the facts from what would be predicted by the theory alone. Rather than abandoning such a theory and the truth that it may embrace, and creating what is analagous to a 'false negative', Type II or Beta statistical error (see Ferguson, 1971, p. 148), the theory can be made to form a model, from which departures can be analyzed in a search for patterns which may lead to an understanding of the other factors that may be involved. This is essentially an analysis of residuals.

The dimensional similarity systems discussed above are models, in that they provide expectant values given proportional changes in every dimension (see McMahon, 1975; McMahon and Bonner, 1983; Ross et al. 1980). Ross et al. (1980) assert that Charles' and Boyle's Laws, relating temperature, pressure and volume of gases, are not laws as much as they are metaphors, or models, which describe how an 'ideal' gas behaves - something that rarely occurs in the real world.

Ross and Wilson (1974) provided kinanthropometry with a very useful model called '*the phantom*', based on departures from '*geometric similarity*' (i.e. where geometric similarity assumes a constant shape over changes in size). The phantom is a unisex reference human, which has a structure (size, shape, proportion) defined by specific anthropometric measurements (e.g. its height is 170.18 cm.). Being unisex, its single scale therefore allows both intra- and inter- gender comparisons, and any sexual bias is eliminated. Each phantom variable is unimodal at 0.00 z-scores, and its variability is defined to be normally distributed. The variables and their distributions are not, however, intended as norms. The phantom is intended as a sample-independent calculation and display device, against which male, female, or various other 'prototypical models' (such as Olympic rowers, for instance) may be displayed and compared.

In using this model to compare individuals, the subject is scaled geometrically to a phantom value (often height, but it could be any other one), using the assumptions of geometric similarity. The equation for this scaling process is provided below:

$$z = \frac{1}{s}[v(\frac{170.18cm}{h})^{d} - P]$$

(Eq. 6)

(Ross et al., 1980, p. 14)

where:

v = the variable measured;
P = the designated phantom value for that variable;
s = the standard deviation from a hypothetical human population for variable v;
$(170.18/h)$ = the scaling ratio, i.e. the phantom stature constant over obtained stature h;
d = a dimensional exponent producing dimensional consistency, (e.g. if v is body mass, d, scaling linear height, is 3);
z = the proportionality value.

The departures of the scaled values from the phantom values describe the proportional difference of the individual from the phantom. While this by itself says nothing, since the phantom is neither real nor representative, comparing the departure scores of two individuals from theoretical expectancy provides a dimensionally 'fair' way of assessing their differences.

An alternative approach uses a theoretical model based not on geometric similarity, but on elastic similarity. This model was derived empirically from observations of many physical structures in the real world, and is generally supported by our knowledge of Newtonian physics. This type of scaling, described by McMahon (1975), uses two length scales instead of just one. Longitudinal lengths, proportional to the longitudinal length scale $[L^1]$, are measured along the axes of long bones. In general, this is the plane in which muscle tensions act, and in which the ever present forces of gravity and the ground reaction force reside. The transverse length scale is called D, is at right angles to L, and therefore represents, and is proportional to, bone and muscle diameters. The proposed relationship between D and L is such that [D] is proportional to $[L^{3/2}]$. McMahon, an engineer, supports this model by showing examples of engineering principles in the bending and buckling of trees, and the structural support of cylinders and beams. The elastic similarity model does not assume a constant geometry or shape, but rather a constant relationship between the length of bodies and the diameters that are required for their support in both static and dynamic self-loading. With [D] proportional to $[L^{3/2}]$, [L] is therefore proportional to $[D^{2/3}]$, and $[L^3]$ is proportional to $[D^2]$. We can now easily derive a new set of relationships or theoretical expectancies for size change in a given dimension. For example, volume, [V], is proportional to $[LD^2]$. By substitution:

$$[V] \propto [LD^2] \propto [L^1L^3] \propto [L^4] \quad \text{and} \quad [L] \propto [V^{1/4}] .$$

Similarly:

$$[D] \propto [L^{3/2}] \propto [V^{1/4}]^{3/2} \propto [V^{3/8}] .$$

Cross-sectional areas are therefore:

$$[D^2] \propto [V^{3/8}]^2 \propto [V^{3/4}] .$$

According to Ross et al. (1984, p. 83), if we assume that volume (V) and mass (M) are in the same dimension, and that metabolic events are related to cross-sectional areas, then this provides an interesting potential explanation for Kleiber's rule regarding basal metabolic rates being proportional to mass$^{3/4}$:

$$VO_2 \propto M^{0.75} .$$

As Ross et al. (1984, p. 84) describe, if McMahon's elastic similarity model were to be adopted as the model for assessing departure scores, the scaling for size differences would have to be different from the Ross-Ward phantom *d*-values. For example, if body weight was chosen as the scaling factor, all lengths parallel to the direction of tension or compression would be scaled with $d = 0.25$; all breadths and girths perpendicular to this direction would be with $d = 0.375$; all support areas would scale to the square of the breadths and girths, which is $d = 0.75$; and all volumes and masses would consist of the product of the length and the area, $d = 1.00$.

It is possible that the theoretical expectancy for some types of performance (e.g. vertical jumps) could be based on a size scaling which uses not geometrical similarity, but elastic similarity, as the departure model. However, an elastic similarity model is more likely to represent the physical constraints that drive the natural selection processes which promote species differentiation across the 'mouse-to-elephant' curve. The relatively small size differences from biological variability within a species, at a given 'snapshot' moment of time, are not likely to show this type of scaling.

For instance, a mouse the size of an elephant would not be able to stand (much less jump) on its skinny legs. Elephants have evolved to be the size they are only because their legs were selected to become proportionately much more massive than those of the mouse. This is not isometric scaling, but a type of allometric scaling which may best be described by an elastic similarity model. Elastic similarity scaling is not being suggested herein as the departure model for describing shape and size variability *within* the human species, however, as there is apparently no evidence to indicate that taller humans have proportionately larger lower extremity girths; i.e. greater than what would be expected by a geometric similarity model. This question is addressed, however, in the analysis of the results of this study (Chapter IV).

Proportional Lower Extremity Lengths:

While proportional lower extremity lengths can be quantified easily using the Ross-Ward (1974) phantom strategy, another potentially useful measure is the *crural index*. Davenport (1933, p. 333) defined it as being, among living subjects, "the projective distance from tibiale to sphyrion divided by the length of the 'thigh'", for which various approaches to measurement were suggested. Kreighbaum and Barthels (1985) described it as being:

> "the ratio of the length of the lower leg to that of the thigh — . A ratio greater than one indicates a leg longer than a thigh; a ratio less than one indicates a leg shorter than a thigh."
>
> (Kreighbaum and Barthels, 1985, p. 58).

They state (without citing specific references but presumably referring to Davenport's 1933 article) that

> "A study of the proportions of animals of different species indicates that the fast runners and jumpers are those that have long distal segments, such as the horse, kangaroo, and the cat. The thigh segment of these animals is short, ending before the segment leaves the pelvis or flank area. The leg segment is longer than the thigh; the foot segment is the longest, and the toes are also quite long. The animals described as the best jumpers have a leg considerably longer than the thigh segment and therefore a large crural index."
>
> (Kreighbaum and Barthels, 1985, p. 58).

It is reasonable to hypothesize that proportionally shorter thighs may result in a reduced moment of inertia around the hip joint, and a faster forward swing of the thigh in running. A proportionally longer leg (shank) may help to lengthen running stride by providing a longer 'reach'. Hay (1985) noted that a given stride length may be more efficiently achieved by a shorter radius of rotation followed by extension of a longer shank (all other things presumably remaining equal).

Kohlrausch (1929) found that Olympic jumpers had a higher mean crural index (1.254) than many other types of athletes (e.g. 1.036 for distance runners). Burke and Brush (1979) found thigh length/total lower extremity length ratios averaging 49% for 13 post-menarcheal teenage female distance runners, as compared with an average of 55% for the same ratio among nonathletic women, reported by Nordgren (1972). This supports the notion that even runners may benefit from larger crural indices. The potential effect on vertical jumping is a subject for consideration in this research.

Extremity and Segment Shape:

Alexander et al. (1981) found that as mammals increase in size, ranging from shrews upwards, they have an increasing proportion of muscle mass to total body mass in the proximal segment of their limbs: i.e., $M_{prox.muscle} \propto M_{total}^{1.1}$. This proximal limb segment muscle mass comprised the hip flexors, extensors, and adductors.

While the proportionality for the proximal limb segment muscle mass was $M^{1.1}$, it was $M^{1.0}$ for the distal limb segment muscle mass (i.e. ankle extensors, deep hind flexors and fore flexors).

Whereas in geometrically similar animals, fibre areas would be proportional to $M^{2/3}$, their calculations show the proportionality to be $M^{0.8}$, for both proximal and distal muscle masses. This was identical to the findings of Maloiy et al. (1979) in their work on the leg muscles of running birds.

Thus larger mammals have proportionally greater fibre areas (and proportionally greater potential strength) in both proximal and distal leg muscle masses. The proportional amount of the proximal leg muscle mass increases with larger mammals, while the distal muscle mass does not. These allometric changes across species are likely to have resulted from the physical requirements of providing stability and locomotion. Otherwise, in geometrically similar animals of increasing size, masses would increase faster than strength, and stability and locomotion would be compromised.

Apart from these differences imposed by size, however, are differences linked to behaviours and performances that have evolved through species differentiation. Ross et al. (1984) summarized how the proportion of muscle mass to total body mass increases from 25 to 30 percent in slow-climbing arboreal animals, to over 45 percent in high-speed terrestrial runners. They also noted that the limbs of these terrestrial animals have become

> "tapered in mass and elongated; the muscular masses are concentrated near shoulder and hip, adaptations which increase stride frequency and reduce the effort during the recovery phase of the step."
>
> (Ross et al., 1984, p. 86).

It appears that the fastest runners and best jumpers among the animal species tend to have delta-shaped extremities with:

1. smaller distal diameters (a lighter mass to transport and swing forward in gait), and;
2. a muscle mass which is concentrated closer to the trunk (with presumeably reduced moments of inertia around the proximal joints, and possibly a longer, stiffer tendon to maximize the storage of elastic energy for improved running efficiency).

What about extremity shape differences within a species? While they are likely to be much less than the differences between species, can they be quantified in a meaningful way, which will then enable extremity shape to be related to performance? Since there does not appear to be a name currently used to describe aspects of *shape* relating to the above discussion of extremity muscularity, the term ***muscle proximorphy*** is herein defined as:

> "the extent to which an extremity's muscle mass (or segment's muscle mass) is concentrated proximally (i.e. closer to the trunk)."

Again, assessment of extremity shape differences across animal species provides a useful framework for creating hypotheses relating to variability within the human species.

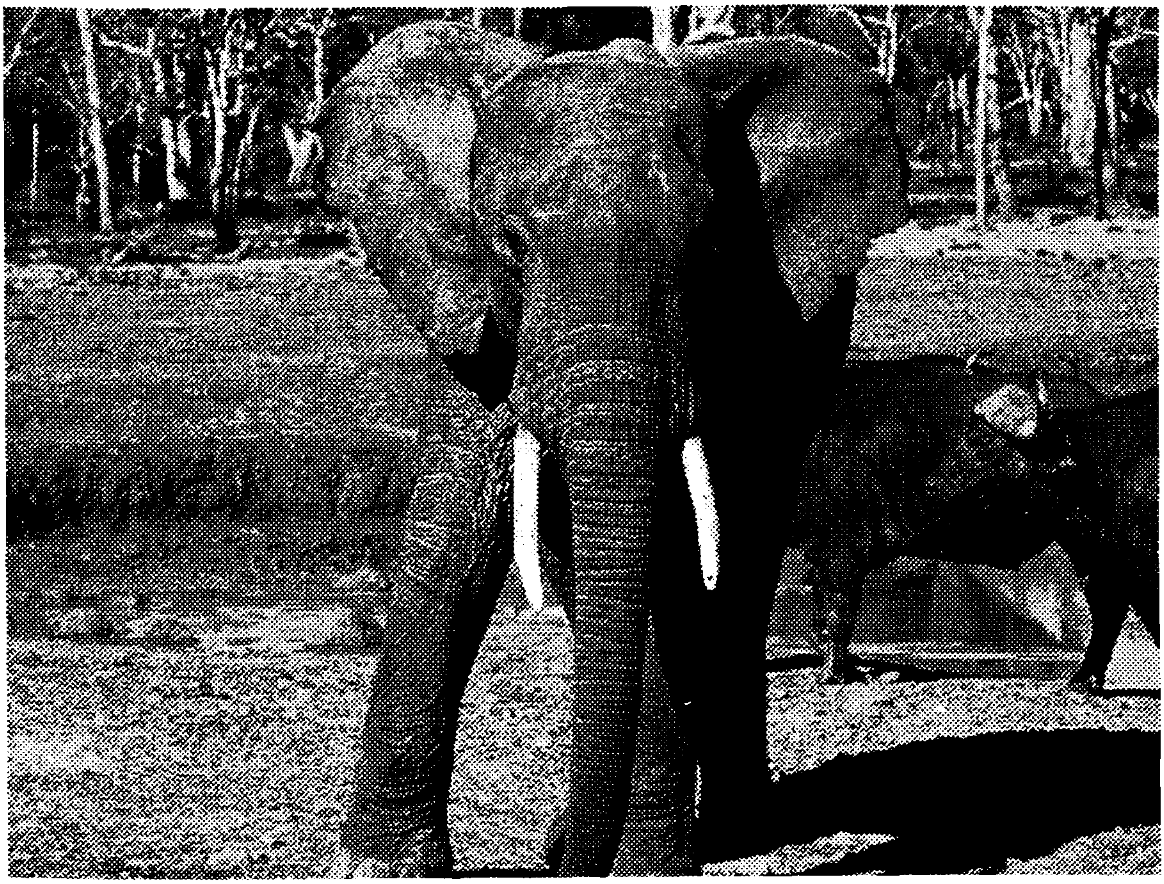

Fig. 2.1: African Elephant (with proportionally massive and cylindrically-shaped extremities). (Photograph by Tom Atwood. © Aris Multimedia Entertainment. Inc., 1993.)

The elephant's proportionally thick and cylindrically-shaped extremities (figure 2.1 above) have evolved through natural selection to fulfill the need for weight support. They are not designed for speed, and do not appear to be as proximorphic as those of the cheetah (which is known to have achieved speeds of over 70 miles (112 km) per hour over short distances). It seems to have proportionally thinner extremities and appears much more proximorphic (see figure 2.2 below). A greater proportion of the lower extremity muscle mass of the cheetah appears concentrated near the trunk.

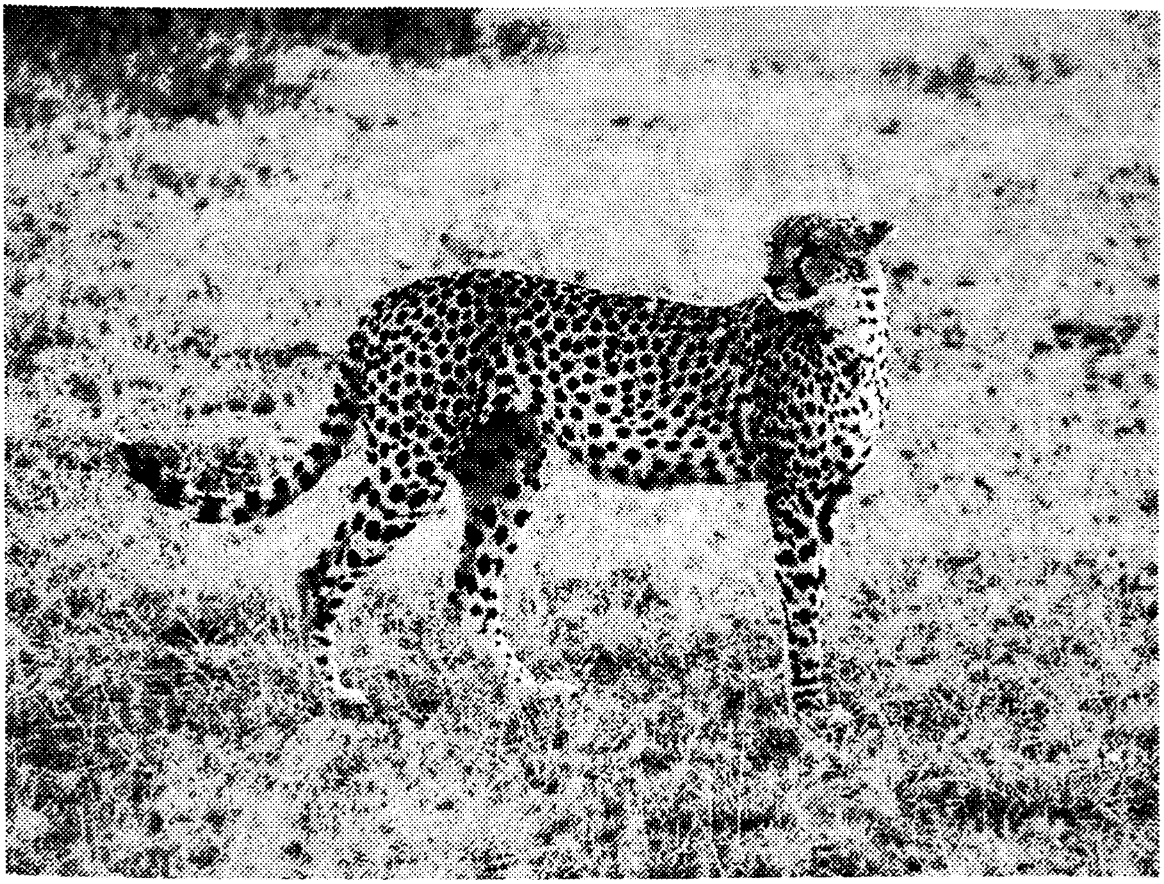

Fig. 2.2: African Cheetah (with proportionally thin and delta-shaped extremities).
(Photograph by Ira Rubin. © Aris Multimedia Entertainment. Inc., 1993.)

In most wild animals, differences in muscle proximorphy are likely to be indicated by the external appearance or shape of the extremities, and could probably be quantified quite well by simply obtaining differences in extremity girths, from proximal to distal sites. Within the more sedentary human species, however, muscle proximorphy may be disguised by a potentially much larger variability in subcutaneous adipose tissue distribution. Human lower extremity proximorphy may be especially confounded by the inclusion of large amounts of adipose tissue on the upper thigh, particularly among females. Therefore, any attempt to quantify muscle proximorphy among human beings, and relate it to physical performance, must attempt to eliminate this adipose tissue in its measurement, thereby separating muscle shape from overall shape. A technique for quantifying human lower extremity muscle proximorphy (i.e. the proximorphic shape of the lower extremity muscle mass) is proposed in Chapter III.

Another, and perhaps more subtle, aspect of extremity shape has to do with the frequency and amplitude of changes in the circumference of each segment, all the way down its longitudinal axis. Body-builders, for instance, have contours that appear to change more frequently, and with greater amplitude, than similarly-sized individuals with poor muscle development. The commonly used terms to describe the subjective perception of this phenomenon are 'definition' and 'cut', and this concept may be related somehow to both the quantity and tonal quality of the muscle in a segment. If a way were found to quantify this aspect of shape, it may also be of some use in predicting jump (and other) performances.

Since there also does not appear to be a scientific term currently used to describe this precise aspect of shape, the term *angularity* is herein defined as:

> "the amplitude of size-dissociated changes in the sequential circumferences of a body segment, integrated down the segment's longitudinal axis."

Segment size and proportionality (to other body segments via phantom comparisons) are already encompassed by the complete proforma used for the Ross-Wilson phantom (1974). Segment shape and intra-segment proportionality, however, are not. Since shape is independent of size, and is based on relationships among proportions, segment shape is dimensionless. Any system for the description of segment shape should therefore allow for the scaling of a given shape to any size. It seems reasonable to suggest, then, that the principles upon which the Ross-Wilson phantom are based could be extended to include extremity and segment shape, including indices for both *muscle proximorphy* and *angularity*.

The Ross-Wilson phantom equation does two things at once:

1. it dimensionally scales a given variable's measurement to dissociate size, and;
2. it standardizes the scaled measurement by taking its deviation from the corresponding phantom model and by dividing this difference by the standard deviation of that variable within a hypothetical human population.

While any approach for describing extremity and segment shape should also dimensionally scale the segment to dissociate size, there are no phantom p and s values for within-segment shape. However, generally similar approaches may still be taken to calculate muscle proximorphy and angularity indices, and the procedures used for this study are described in Chapter III.

Section 2 - JUMPING

Kinetics of Jumping:

NOTE: In the following discussion, two assumptions are made for convenience:

1. Animals seldom jump in a purely vertical direction. The following discussion is delimited, however, to the vertical component of the force, displacement, velocity and acceleration vectors. This is of course determined by multiplying the vector magnitude by the sine of the angle which the vector makes with the horizontal. Obviously, the greater the proportion of a given vector that occurs along the horizontal (x or y) axes, the smaller the proportion that remains along the vertical (z) axis.

2. The term 'jump height' can variously mean the height cleared in a jump, the height one can reach in a jump above a standing reach height, etc.. It is a non-specific term that must be operationally defined when used. Herein, it will be used to indicate the vertical displacement of the centre of mass of a jumping animal; i.e. the maximal increase in vertical height of its centre of mass above where it was at the moment of take-off (i.e. where the take-off velocity was achieved). Note that this is only for the vertical (z) axis:

   Jump Height - *the maximal increase in the height of the centre of mass above its take-off height.*

To understand how an animal jumps, we must first look at how it stands. Newton's First Law of Motion (The Law of Inertia) can be expressed as follows:

> "Every body continues in its state of rest or motion in a straight line unless compelled to change that state by external forces exerted upon it."
> (Hay, 1985, p. 59)

The centre of mass of an animal standing on the ground will thus remain forever at a state of rest unless acted upon by external forces. On earth, of course, one external force (gravity) is always acting upon all objects, accelerating them downward unless countered by other forces.

Newton's Second Law of Motion (The Law of Momentum) may be stated as follows:

> "The rate change of momentum of a body (or the acceleration for a body of constant mass) is proportional to the force causing it and the change takes place in the direction in which the force acts."
> (Hay, 1985, p. 61).

Expressed mathematically,

$$F \propto \frac{d}{dt}(mv)$$

(Eq. 7)

where:

F = force;
m = mass;
v = velocity = $\frac{d}{dt}x$ (where x = displacement);
mv = momentum;
t = time.

For a body of constant mass, this becomes

$$F \propto m\frac{d}{dt}v$$

(Eq. 8)

or, since the change in velocity per unit time is acceleration, by substitution

$$F \propto ma$$

(Eq. 9)

and

$$F = kma$$

(Eq. 10)

where k is a constant.

When we use Newtons as our unit of force (a force of one Newton will produce an acceleration of 1 metre per second per second on a 1 kilogram mass) the constant k becomes 1, and can be omitted. Thus the centre of mass of the animal will, barring other forces, be accelerated downwards by the force of gravity, according to the formula:

$$F = ma$$

(Eq. 11)

or, more specifically,

$$W = mg$$

(Eq. 12)

where:

W = weight (the force of gravity acting on a mass, expressed in Newtons);
m = mass in kg;
g = acceleration due to gravity of 9.81 meters/second^2 (abbreviated m/s^2).

The force of gravity acting on a standing animal causes torques at the spine, hip, knee, and ankle. By themselves, these torques would produce angular accelerations of these joints, and hip and knee flexion and ankle dorsi-flexion would result in the acceleration of the animal's centre of mass downwards in collapse. A standing animal must therefore provide force, and opposing torques at the joints, the net of which must be equal and opposite to those produced by gravity. The animal therefore uses hip extensor, knee extensor, and ankle plantar flexor muscles to generate (isometrically) these opposing torques. This results in a downward force against the ground. The equal and opposite 'ground reaction force' (*GRF*) is directed upwards, and counters the downward force of gravity. If the vertical component of the *GRF* is less than W in absolute magnitude at any point in time, the animal's centre of mass will be accelerated downwards. If the *GRF* is more than *W*, the centre of mass will be accelerated upwards.

If the animal wishes to jump, the *GRF* must obviously begin to exceed *W*. However, instantaneous maximal *GRF* is not the crucial factor in the vertical jump. While a great force may produce a large acceleration on a given mass ($F = ma$), that force must continue over a period of time if any momentum (i.e. *mass X velocity*) is to be developed, and if a take-off velocity is to be achieved.

For an object with a constant mass and an initial velocity of 0:

$$\int F dt = m v_f$$

(Eq. 13)

where:

v_f = final velocity (i.e. takeoff velocity);

or,

IMPULSE = CHANGE IN MOMENTUM, or

IMPULSE = MASS x FINAL (TAKEOFF) VELOCITY
(given constant mass and an initial velocity of zero)

Thus the force of gravity, acting over time, produces a downward-directed impulse, while the ground reaction force derived from the subject, also acting over time, produces an upward-directed impulse. The net difference will produce a change in velocity in the direction of the greater impulse. When a jump occurs, the vertical velocity at take-off will be determined by the upward impulse from the GRF minus the downward impulse from mg.

$$\int (GRF)dt - \int (mg)dt = mV_{takeoff}$$

(Eq. 14)

As is shown below, it is the vertical 'takeoff velocity' which is effectively the sole factor in determining the height to which the centre of mass of a large animal rises.

When the animal has left the ground, further upward forces can no longer be created. While some insects and birds with wings can generate enough force against the air to substantially increase their upward-directed impulse and 'fly', the small air reaction forces that larger animals can exert, over body surface areas that are relatively much smaller than wings and against proportionally much greater weights [L^3], preclude this possibility.

The small air resistance force that does exist is directed against the motion of the jumping animal, and is increased with the animal's velocity. On the way up, air resistance is directed downward and is decelerating the jumper along with gravity. Its magnitude is greatest at take-off, when upward velocity is maximal, and it diminishes to zero at the apex of the jump, when the subject's velocity is also zero. On the way down, the air resistance is directed upward and acts against the subject's acceleration due to gravity, reducing it to something theoretically less than 9.81 m/s^2. Air resistance starts at zero at the peak of the jump, and increases throughout the descent as the jumper accelerates due to gravity.

Air resistance has a greater effect on smaller animals, and in fact becomes the dominant influence in the smallest of jumping animals such as the flea. A simple dimensional analysis explains that a small animal has a larger surface area per unit mass than a larger animal of the same proportions, and this results in the smaller animal having a much greater aerodynamic drag relative to its momentum. While air will absorb 10% of the energy in a jump 1 metre high by an animal 0.1 metre long, it will absorb 50% of the energy in a 0.1 metre jump by an animal 1 mm long (Bennet-Clark, 1977). (A smaller animal can of course travel a greater proportion of its body length than does a larger one, sometimes achieving jump heights over 100 times body length.)

As animals increase in size, their masses increase more quickly than their surface areas, and air resistance becomes an insignificant force in the performance of a jump. Since this research is focussed on human vertical jumping, air resistance factors will not be considered further herein.

As a result of air propulsive and resistive forces being inconsequential during a larger animal's jump, the animal therefore behaves in the air according to the laws of constant acceleration. Gravity acts downward to decelerate the jumper until the upward velocity reaches zero at the apex, at which point gravity then becomes a motive force to accelerate the animal in a downward direction at a theoretical 9.81 m/s^2, until the ground is again reached.

Discounting air resistance, the vertical distance that the centre of mass of a jumping animal (or any other projectile) will travel while airborne, may be determined by the following equation derived from the 'conservation of energy' law:

$$d_v = \frac{v_v^2}{2g}$$

(Eq. 15)

where:

d_v = the vertical displacement (upwards);
v_v = the vertical velocity component at take-off;
g = the acceleration due to gravity (i.e. 9.81 m/s^2).

The derivation of this equation comes from an analysis of the energy of a body. Energy can be defined as

> "the capacity to do work"
>
> (Blatt, 1989, p. 84).

Mechanical energy is that which a system may have

> "by virtue of its position, its internal structure, or its motion"
> (Blatt, 1989, p. 84).

Two types of mechanical energy change throughout a jump: kinetic and potential energy

Kinetic energy can be defined as

> "the energy that a body has because it is moving"
> (Hay, 1985, p. 97)

and can be described by the equation

$$E_k = \frac{1}{2} m v^2 \qquad \text{(Eq. 16)}$$

where E_k = kinetic energy

Potential energy can be defined as

> "the energy due to the position that a body occupies relative to the earth's surface"
> (Hay, 1985, p. 98)

and can be described by the equation

$$E_p = m g h \qquad \text{(Eq. 17)}$$

where:

E_p = potential energy;
h = height above the ground.

The Law of Conservation of Mechanical Energy may be stated as follows:

> "When gravity is the only external force acting on it, the mechanical energy of a body is constant."
>
> (Hay, 1985, p. 99).

If we assume that a vertical jump from the ground begins with 0% potential energy and 100% kinetic energy, and results at its apex in 0% kinetic energy and 100% potential energy, the Law of Conservation of Mechanical Energy allows us to form:

$$E_k = E_p$$

(Eq. 18)

where:

E_k = kinetic energy upon leaving the ground;
E_p = potential energy at the apex of the jump.

or, by substitution,

$$\frac{1}{2} m v_v^2 = mgh$$

(Eq. 19)

or:

kinetic energy on leaving the ground = potential energy at the apex.

Solving for *h*, we obtain

$$h = \frac{v_v^2}{2g}$$

(Eq. 20)

which, since "height" here is the same as "vertical displacement" jumped, is virtually the same as equation fifteen above.

To jump upwards 1 metre, an animal must achieve, at its centre of mass, a vertical take-off velocity of 4.4 m/s^2, irrespective of its size. If it can achieve twice the speed, it will reach 4 times the height, since the height attained is directly proportional to V^2.

Finally, we may wish to estimate the height jumped from the time spent in the air. From the equations of ***uniformly accelerated motion*** we have:

$$d_v = v_i t + \frac{1}{2} g t^2$$

(Eq. 21)

where:

d_v = vertical displacement;
v_i = initial velocity;
g = acceleration due to gravity;
t = time.

During a jump, if the centre of mass lands at the same height from which it takes off, the time moving upwards (t_u) equals the time moving downwards (t_d). (The acceleration due to gravity is constant, whether moving up or down. For a fuller description, see Hay, 1985, p. 35). Thus the total time in the air, T, will equal t_u plus t_d. Substituting in equation 21 (above) to determine the displacement downward (d_v) from the apex (where $v_i = 0$), we get

$$d_v = \frac{1}{2} g \left(\frac{1}{2} T\right)^2$$

(Eq. 22)

and, simplifying,

$$d_v = \frac{gT^2}{8}$$

(Eq. 23)

where:

T = total time in the air,
d_v = displacement down = absolute value of displacement up (again, assuming the landing height of the centre of mass is the same as its take-off height).

This estimate is based, as stated, on the assumption that the animal's centre of mass takes off and lands at the same height above the ground - an assumption which leaves some potential for error. For instance, a human subject who knows that the jump displacement estimate is based on the time spent in the air, may pull the legs up when landing, slightly increasing the air time and producing an overestimate of the real jump displacement. Even without this conscious attempt to 'cheat', a normal jump will involve a take-off with the ankles plantar-flexed and the body extended upwards, while the landing may involve less plantar-flexion and a somewhat flexed trunk, hips and knees in preparation for shock absorption. In other words, the centre of mass in this case would have a lower landing height than the take-off height, and the air time would again overestimate the jump's vertical displacement. (In this study, the jump height estimated from air time was compared to the criterion; i.e. that calculated from the net upward impulse.)

Dimensionality of Jumping:

At first glance, by way of a simple unit analysis, the dimensionality of a vertical jump appears to be $[L^1]$. From equation twenty

$$h = \frac{v_V^2}{2g}$$

$$[L^1] \propto ([L^1/L^1]^2 / [L^1/L^2]) \propto [L^1].$$

However, $2g$ is a constant (at least in one geographic location) and does not change as the size of an animal changes. When scaling jump height expectations for size changes, $2g$ does not play a role. Without that, v^2 itself is a dimensionless $[L^0]$.

This is not a new idea. Giovanni Alphonso Borelli (1608-1679) noted that geometrically similar animals jump to the same height regardless of their size (see Ross et al., 1984). In this century, A.V. Hill (1950) put forth a similar argument in a paper entitled "The dimensions of animals and their muscular dynamics". The argument is summarized below.

The work done by a muscle is equal to its force, which is proportional to the cross-sectional area of the muscle $[L^2]$, multiplied by the distance through which it shortens $[L^1]$.

$$Q = Fd$$

and (Eq. 24)

$$Q \propto [L^2][L^1]$$

$$Q \propto [L^3]$$

where:

Q = the work done by the muscles as they shorten $[L^3]$;
F = the force which they exert, proportional to their cross-sectional area $[L^2]$;
d = the displacement of its shortening, assumed for a fixed strain to be proportional to the extended length of the muscle $[L^1]$.

If we make the assumption that it is all turned into increased potential energy, raising the animal's weight $[L^2]$ through height h $[L^1]$, then,

$$Q \quad mgh \qquad \text{(Eq. 25)}$$

Rearranging equation twenty-five, we have

$$h \quad Q\,mg \propto (\,[L^2L^1]\,/\,[L^3L^{-1}]\,) \propto [L^1] \qquad \text{(Eq. 26)}$$

Since Q scales directly with m, and g is unaffected by m, h scales with $m\ m$ or L^0.

In an overview entitled "Physics and the Vertical Jump", Offenbacher (1970) provides another simple derivation which supports the notion that a vertical jump is dimensionless. He notes that displacement of the centre of mass occurs in two phases:

1. the stretching segment - i.e. the ground contact phase, from a crouched position to take-off, during which time the ground reaction force is generated;

2. the free flight path - i.e. the vertical displacement in the air, the length of which is determined by the take-off velocity^2 (Eq. 15), which in turn has resulted from the net upwards-directed impulse from the GRF in phase one (Eq. 14).

In other words, phase two (the jump displacement) is entirely dependent on the final velocity (take-off velocity) obtained in phase 1. Offenbacher looks at the *average* acceleration which occurs from the crouched position at the beginning of phase 1 to the take-off position at the end of phase 1. This enables us to use the following equation for uniform acceleration, even though acceleration is not uniform:

$$v^2_f = v^2_i + 2ad$$

(Eq. 27)

where:

v_i = the initial velocity (0 m/s) at the beginning of the 1st phase;
v_f = the take-off velocity at the end of the 1st phase;
a = the *average* acceleration during that period;
d = the upward displacement (of the centre of mass) during that period.

Since the initial velocity is 0 m/s, v^2_i can be eliminated. Also, since $a = F/m$ (Eq. 1), we can substitute "(average force)/mass" for "average acceleration". We then have

$$v^2_f = 2(\overline{F}/m)d$$

(Eq. 28)

and

$$v^2_f \propto [L^2/L^3]\,[L^1]$$

(Eq. 29).

In other words, jump displacement in the flight phase, dependent upon v^2_f, is in turn dependent on two factors:

1. an *average force mass* ratio $[L^2/L^3] = [L^{-1}]$;
2. a *displacement* through which acceleration can occur on the ground $[L^1]$.

The product of these two is dimensionless $[L^0]$.

So if a vertical jump is dimensionless and cannot be scaled for size among geometrically similar animals of varying sizes, what is the point of research into attempting to predict human vertical jump from aspects of size?

The argument proposed here involves a perspective change from biology to kinanthropometry. Below, a previously used quotation is repeated:

> "Although comparisons between species often show a regular change in shape with increasing size, comparisons among different-sized individuals of the same species generally reveal a reasonably faithful isometry."
> (McMahon and Bonner, 1983, p. 51)

Biologists, who may study allometric relationships among species with hugely varying structures along the 'mouse-to-elephant' curve, understandably view structure within a species as being reasonably isometric. Kinanthropometrists, however, focus their discipline on quantifying the variability they see *within* the human species. While structural variability among humans is, of course, not on the scale of the 'mouse-to-elephant' curve, it is still substantial and can be relatively easily quantified. It *may* be possible to scale vertical jumps for changes in size when those changes are concomitant with changes in geometry (i.e. when size change is allometric rather than isometric). Some of the guiding principles, however, may still come from the allometry of biology.

Allometry of Jumping:

From equations 17 and 18, we derive

$$h = \frac{E_k}{mg}$$

(Eq. 30)

where:

h = the vertical displacement (height) jumped,
E_k = the kinetic energy at take-off;
mg = body weight.

In other words, the kinetic energy per unit mass, imparted to an animal by its muscles, will determine the height of the jump. The energy required for jumping a given height is again shown to be independent of size, assuming no change in the proportions or densities of the various tissue masses. Bennet-Clark (1977, p. 187) suggests that if all animals had the same proportion of involved jumping muscle to total body mass (an assumption which kinanthropometrists may find difficult to accept), and that if all their muscles had equal capability for producing the same kinetic energy (an assumption which may not find favour with exercise physiologists), then they should all jump to the same height. (The implication is, of course, that variability in the muscle proportion of body weight and the qualitative characteristics of the muscle may cause variability in jump height! A larger proportion of muscle mass per unit of body weight should provide more kinetic energy, leading to a greater jump height, if the characteristics of the muscle remain constant. This is another topic addressed in the results of this study, in Chapter IV.)

From equations 28 and 29, it was shown that the dimensionless but ultimately important *take-off velocity*^{2} was dependent upon two factors:

1. a *force mass ratio* $[L^2/L^3] = [L^{-1}]$;
2. a displacement through which acceleration can occur on the ground $[L^1]$.

Smaller animals, with shorter distances available for acceleration $[L^1]$, should theoretically be able to compensate for this by having larger "force/mass" ratios $[L^{-1}]$. There are limits to this ability to compensate, though, since high muscular forces ultimately require greater skeletal mass (Bennet-Clark, 1977). The force/mass ratio thus has a "ceiling effect" limitation, while the acceleration distance has no equivalent "floor effect" limitation.

Bennet-Clark (1977) further suggests that in order to minimize the requirement for skeletal strength, and thus the requirement for skeletal mass, it is advantageous for the force, F, to be constant throughout the jump impulse. This would maximize impulse ($\int F dt$) for a peak force limit, and provide a constant acceleration (i.e. a linear increase in velocity) to take-off. However, he states that with all animals, but especially small ones, direct muscular contraction is not able to produce a constant force over a wide range of velocities. This is discussed in detail, with respect to human muscle, by Abbott and Wilkie (1953) and Chapman (1985).

Similarly, from equation 13 we obtain

$$\Delta v = \frac{\int F dt}{m}$$

(Eq. 31)

The take-off velocity (the determining factor in jump height achieved) is thus dependent upon the net vertical impulse/mass ratio, and since constant forces are not feasible, the ability to create and withstand large peak forces is a limiting factor. (Peak forces are also addressed in the results in Chapter IV.)

Pennycuick (1992, p. 42) notes that

> "Popular accounts credit the flea with spectacular powers because it can jump many times its own body length, but that is irrelevant. The *absolute* height of the jump should be independent of the mass, not the height relative to the body length. Fleas can jump less than 5 cm straight up, ... , one has to ask why their performance is so wretchedly inadequate, in comparison with that of mammals."
>
> (Pennycuick, 1992).

In pointing out that terrestrial animals of all sizes jump, Bennet-Clarke (1975 and 1977) emphasizes that since the smaller animals have shorter limbs and diminished ranges (i.e. distances) through which they can apply their forces for acceleration, they have less time and distance to develop the impulse required to attain high take-off velocities. Bennet-Clark and Lucey (1967) estimated that fleas only have about 0.75 milliseconds for this to occur. Forces and accelerations must be much greater in these smaller animals in order to achieve the same take-off velocities. Bennet-Clarke (1977) states that while a leopard need only produce forces of about 1.6 times its body weight to make a normal jump, a flea, jumping only about 1/10 th as high, must produce forces about 200 times its body weight. These much higher forces have to be withstood by their structures, and the internal organs must be able to cope with the much higher accelerations.

Bennet-Clark and Lucey (1967) discovered that a flea's muscles, instead of extending the legs directly, distort a piece of rubber-like protein which acts as a spring, and quite slowly stores the work done by the muscles. When the flea needs to jump, a small muscle operates a trigger mechanism which releases the spring, allowing the stored energy to explosively extend the legs. This protein can apparently change its shape at a much higher rate than would be possible for a muscle, and the spring then catapults the flea into the air. However, the weight of this protein spring, along with the increased effects of air resistance, diminish the height of the jump from what it would otherwise be.

Not only must the force be greater in small animals, but the peak power that is required must increase with decreasing size. The peak power required increases as the 3/2 power of the height of the jump, so to jump twice as high, the animal must produce twice the energy and 2.8 times the peak power (Bennet-Clark, 1977, p. 188)

From physics:

$$P = \frac{d}{dt}Q = \frac{d}{dt}(F \bullet d) = F \bullet v = mav$$

(Eq. 32)

where:

P = instantaneous power;
Q = work;
t = time;
F = force;
d = displacement;
v = velocity;
m = mass;
a = acceleration.

Bennet-Clark provides a scaling equation for the height of a jump across species, with respect to the animal's length and the peak power output of its muscle:

$$h = \left(\frac{2sP}{m}\right)^{\frac{2}{3}} * \frac{1}{2g}$$

(Eq. 33)

(Bennet-Clark, 1977, p. 192)

where:

s = the distance for acceleration (assumed to be proportional to the animal's length);
P = peak power output of the muscle;
m = the animal's mass;
g = the acceleration due to gravity.

Since he did not provide a derivation for this equation, one is provided below.

From equation 32;

$$P \quad m\,a\,v$$

from equation 27, where d is s,
and substituting for a $\quad v^2\ 2s$;

$$P \quad \frac{m\,v^2\,v}{2s}$$

from equation 20, where $v^2 \quad 2gh$,
and substituting for v^2 and v;

$$P \quad \frac{m\,2\,g\,h\,2^{1\ 2}\,g^{1\ 2}\,h^{1\ 2}}{2s}$$

rearranging and simplifying;

$$s\,P \quad m\,g\,h\,2^{1\ 2}\,g^{1\ 2}\,h^{1\ 2}$$

squaring both sides of the equation;

$$s^2\,P^2 \quad m^2\,g^2\,h^2\,2\,g\,h$$

simplifying;

$$s^2\,P^2 \quad m^2\,g^3\,h^3\,2$$

rearranging to isolate h^3;

$$h^3 \quad \frac{s^2\,P^2}{m^2\,g^3\,2}$$

taking the cube root of each side;

$$h \quad \frac{s^{2\ 3}\,P^{2\ 3}}{m^{2\ 3}\,g^{3\ 3}\,2^{1\ 3}}$$

multiplying each side by $(2^{2\ 3}\ 2^{2\ 3}) \quad 1$

$$h \quad \frac{s^{2\ 3}\,P^{2\ 3}\,2^{2\ 3}}{m^{2\ 3}\,g^{3\ 3}\,2^{1\ 3}\,2^{2\ 3}}$$

and simplifying;

$$h \quad \left(\frac{2sP}{m}\right)^{2\ 3} * \frac{1}{2g}$$

Bennet-Clark states that s is likely to be proportional to the animal's total length, l, and that p is proportional to the mass of muscle involved (somewhere between 5 and 20% of a small animal's total mass). Therefore h is proportional to $l^{2/3}$, with a constant of proportionality dependent upon the specific power output of the muscle.

Equation 28 (from above) explains how the square of the take-off velocity is dependent upon the ratio of the *average* vertical component of the ground reaction forces over mass, times the vertical displacement through which the centre of mass moves during ground contact.

$$v^2_f = 2(\bar{F}/m)d$$

(Eq. 28)

Also, since

$$h = \frac{v_v^2}{2g}$$

(Eq. 20)

we can substitute and rearrange

$$h = \frac{\bar{F}d}{mg}$$

(Eq. 34)

For a given weight (mg), the height achieved in a jump (i.e. the vertical displacement of the centre of mass) will be dependent upon the product of the average vertical component of the ground reaction forces and the vertical displacement through which the centre of mass moves during the period of ground contact. Sanders and Wilson (1992) refer to this displacement in human jumping as the *movement amplitude* of the jump.

In summary, *d* is a displacement of the centre of mass of a jumper during the extension stage, when the GRF is performing work on the jumper. From equation 33, we can see that the height (*h*) of a jump is proportional to $d^{2/3}$ if the constant of proportionality is the power output of the muscle. On the other hand, from equation 34, we can see that *h* is directly proportional to *d* if the co-factor being considered is force.

Since *d* is generally proportional to the length of an animal (and *may* be proportional to the stature or lower extremity length of a human) these considerations are important when constructing theoretical models for the prediction of vertical jump from anthropometry.

According to the classic force-velocity curve of Hill (1938), contraction velocity is maximal when muscle is unloaded and falls to zero at the isometric load, forming a rectangular hyperbola in between. Hill (1950) showed that, at least for fast-type muscles, power output appears to be maximized at about 1/3 isometric force and 1/3 peak velocity of shortening. Operating at maximum power results in only 1/3 of the maximal potential work being done in a single contraction, at a much slower than maximal speed of contraction. Since the smaller animals have less time to accelerate, and therefore have to contract their muscles more rapidly, maximum power is compromised.

Bennet-Clark (1977, p. 192) asserts that there is good circumstantial evidence that many small animals, especially below a body length of about 1 metre, store the energy for their jumps the way fleas do, and then release it rapidly through a similar type of 'power amplifier'. Even some larger mammals rely heavily on storage energy for locomotion (Biewener et al., 1981). The simplest mechanism involves the storage of energy as tendon tension - for example, the kangaroo, which has a cylindrical collagen Achilles tendon which stores and returns the kinetic energy of the up-and-down bouncing which is characteristic of their gait (Dawson and Taylor, 1973; Morgan et al., 1978; Alexander and Vernon, 1975).

In general, then, larger animals may have one advantage in jumping, in that their impulse can be developed over a longer displacement, thereby reducing the need for such high forces as are required among the smaller animals. In theory, length differences by themselves should have the same effect within a species, if all jumps were to occur from the same degree of lower extremity joint flexions. Whether or not this plays a role among humans of different statures and lower extremity lengths is addressed in the results contained in Chapter IV.

Natural selection will normally encourage the replication of those sizes and shapes which are best able to optimize 'impulse-mass-length' trade-offs. As Ross et al. note (1984, p. 86):

> "— even moderately sized animals have colonized the ground (from arboreal environments), with a significant shift in their locomotor capacities; greater speed and acceleration and the tendency to strengthen lower back and hind limbs. The limbs become tapered in mass and elongated; the muscular masses are concentrated near the shoulder and hip, adaptations which increase stride frequency and reduce the effort during the recovery phase of the step. Animals as diverse as kangaroos, jack rabbits, and greyhounds — may become more than 45% muscle."

It may ultimately come back to haunt us (if it has not already done so) that humans, through the adaptive workings and technologies of modern societies, have effectively withdrawn from the constraints of natural selection, and the biological need for physiques optimized for wilderness survival apparently no longer exists. Perhaps only athletes retain vestiges of the physical characteristics that would provide us with a perspective of our naturally evolved place along the 'mouse-to-elephant' curve.

Human Vertical Jump Research:

HISTORICAL PERSPECTIVE:

It was more than a century ago when Marey and Demeny (1885) first studied changes in reaction force and corresponding body positions during a standing jump with a dynamograph and a photochronograph (which provided successive images on a single photograph). Much later, Gerrish (1934) recorded vertical jump height and pressure gauge information read from 16 mm film through a microscope. In between, field tests for jumping ability became extremely common and well documented.

A vertical jump field test, also called the 'jump and reach' test, has been used in its many variations since at least the end of the last century (see DA Sargent, 1921; LW Sargent 1924; McCloy, 1932; Bookwalter, 1943; Phillips, 1947; Fleishman, 1964). The 'Sargent Jump', as it came to be known by the physical educators, coaches and athletes who used it, has often been assumed to be a measure of leg *power* (Sargent, 1921; Klotz, 1948; Gray et al., 1962; Lightsey, 1985; Barham et al., 1985). (The rationale, and opposing arguments, are described in the next section, THE VERTICAL JUMP AS A TEST OF POWER.)

The Sargent jump test was originated by D. A. Sargent (1921), and was first validated by L. W. Sargent (1924), who called it a test of "neuromuscular efficiency involving strength, speed, coordination, and driving power." It was also validated by Collins and Howe (1924), Bovard and Cozens (1928), and McCloy (1932). McCloy stated that it was the best single test available for predicting 'power'. In a factor analysis study, Coleman (1937) found the test to be loaded .29 with 'force' and .58 with 'speed'. Harris (1937) found similar but higher loadings on junior high school girls, at .33 and .73 respectively. McCloy (1932) found a correlation of .651 with the 100-yard dash among senior high school boys, while Van Dalen (1940) found the correlation to be .810 on a similar group of subjects.

There have been many variations in the administration of this test over the years, some of which have been summarized by Van Dalen (1940). However, a common format has been described by Bosco and Gustafson (1983, p. 90) and is presented below, in the imperial units by which it was described.

Equipment:

A plywood board measuring 2 feet wide X 5 feet high is painted flat black with yellow lines one inch apart extending horizontally across the width of the board. The lines are numbered from 70 at the bottom to 130 at the top. The board is attached firmly to the wall, preferably six inches away from it, with line 70 placed exactly 70 inches above the floor. Chalk for the fingertips is required.

Procedures:

Chalk is placed on the fingertips of the dominant hand. The subject faces the board, reaches to a maximum height without lifting the heels, and marks the maximum height to the fingertips. The fingertips are re-chalked and, with the dominant side to the wall, a jump is made straight upward. Another mark is made at the top of the jump with the same hand used in measuring the standing reach height. No run or preliminary hop or step is allowed. The subject may bend the knees and swing the arms preparatory to the jump.

Scoring:

The score is the difference between the standing reach height and the jumping reach height. Three trials are allowed and scored to the nearest quarter inch.

Reliability:

Glencross (1966) found a test-retest reliability of .92 on 85 male college students. Fleishman (1964, p. 59) calculated a coefficient of .90 on 201 male college students averaging 18 years of age. Cureton (1964, p. 172), however, reported a relatively low coefficient of only .78 for 74 young boys 7-13 years old. The more inconsistent results found on these and other young children may reflect lower skill and coordination levels, difficulties with motivation, etc.. With older age groups, the reliability of the test appears to be very good.

Validity:

'Face' validity is most often claimed for the vertical jump test as a test of power, although some attempts have been made to validate the vertical jump as a measure of leg muscle power by correlating it with external criteria. McCloy (1946, p. 59-61) conducted a series of studies in which the vertical jump was correlated against a battery of four track events. Validity coefficients ranged from .65-.93 for men and boys and from .60 to .88 for girls. On the basis of these and other studies, he concluded that the vertical jump, if combined with age and size or some measure of strength, could be used to predict certain track and field abilities.

Glencross (1966) reported a validity coefficient of .73 when the vertical jump was correlated against a battery of four power tests measured with a power lever (a pulley device that can measure the average horsepower developed in a variety of single, explosive movements).

Norms:

Norms based on height-weight classes are available for elementary and junior high school boys and girls (Neilson and Cozens, 1934, p. 54-55; 118-119), and for high school and college women (Cozens et al., 1939, p. 64). Cureton (1964, p. 193) has provided norms for boys aged 7-13 years, while Johnson and Nelson (1969, p. 82) have published them for boys and men, 9-34 years; and girls and women, 9-34 years.

Skill Factors:

When lab tests using force platforms or kinematic analyses are not possible, field tests such as that described above have to be used. What is usually measured is the height of the reach of the hand from the ground at the peak of the jump, from which is subtracted the height of the reach of the hand from the ground in a standing position. This vertical jump 'reach' height is dependent upon three factors:

1. the height of the centre of mass (CM) from the ground at take-off;
2. the vertical velocity of the CM at take-off;
3. the vertical distance of the fingertips relative to the CM at the peak of the jump.

(modified from Kreighbaum and Barthels, 1985, p. 348)

1. Height of the CM from the ground at take-off:

If two objects are projected from different heights with the same vertical velocity, the one projected from the greater height will reach a higher peak. Similarly, the body's centre of mass (CM) will reach a higher peak relative to the ground if it is higher at take-off, provided that the attainment of that greater height has not had a deleterious effect on the vertical velocity of the CM at take-off. Since the body's CM on the ground can be modified by relocating body segments, it follows that vertical jumping technique may play a part in maximizing the height of the CM from the ground at take-off, and thus the overall jump 'reach' height.

The use of the arms is an obvious example. Swinging the arms upward to a shoulder-flexed, vertical position has the effect not only of creating momentum, which can presumably be transferred to the body when shoulder-flexion ceases, but also of raising the body CM by a few centimetres just prior to take-off (Kreighbaum and Barthels, 1985, p. 349). In a similar manner, complete hip extension, knee extension and ankle plantar-flexion serve not only to maximize the impulse generated by each of these joints, but also to maximize the height of the CM at take-off. While in a normal subject, hip and knee extension are not anatomically limited in obtaining full extension, individual differences in ankle plantar-flexion range of motion may be considerable, and could have an over-all effect on the jump height attained.

2. Vertical velocity of the CM at take-off:

Discussion above showed how vertical velocity is critical to determining jump height. While good technique can of course do nothing to diminish *W*, it can at least ensure that the CM remains in alignment with the *GRF*. If the ground reaction force becomes eccentric to the CM, some degree of body rotation will be produced and vertical velocity of the CM will be diminished. An important aspect is the coordination and timing of the output of the muscles (see Bobbert and Van Ingen Schenau, 1988), which is assumed to be task-specific and an improveable skill. The remaining sections of this chapter discuss the existing research pertaining to the factors involved in maximizing the vertical velocity of the CM at take-off.

3. Height of the fingertips above the CM at peak CM height:

While free of support, a jumper can have no effect on the location of the body CM or its predetermined flight path from take-off. However, body parts may be re-located around the CM as far as the range of motion of the joints will allow. A vertical jumper may be able to gain a few centimetres of 'reach' height advantage by dropping one arm to the side just prior to the peak of the jump, thereby causing the upper body to rise around an unchanging path of the CM (see Kreighbaum and Barthels, 1985, p. 350).

A combination of two factors will result in jump heights determined from this type of field test being considerably more than those resulting from similar jumps on a force platform:

1. The standing reach height (which is subtracted from the jump reach height) is taken from a normal standing position with the heels on the floor (i.e. the foot is not plantar-flexed as at take-off). This probably increases the calculated field test jump height over the real height gain of the CM by several centimetres.

2. While the pathway of the CM cannot be altered in the air, a skilled performer in the field test may drop one arm in order to raise the other one higher and achieve a greater jump reach. This does not normally happen when jumping on a force platform.

THE VERTICAL JUMP AS A TEST OF POWER:

Average power is defined as the work performed over the time taken to perform it, while *instantaneous power* is the rate of work performed. Since work is the product of force and displacement, substitution gives us power being equal to the product of force and displacement divided by time. With displacement over time being velocity, power is therefore also equal to force times velocity, or, in lay terms, strength times speed, or 'explosive strength'. Mathematically, this was shown by equation 32.

$$P = \frac{d}{dt}Q = \frac{d}{dt}(F \bullet d) = F \bullet v = mav$$

(Eq. 32)

where:

P = instantaneous power;
Q = work;
t = time;
F = force;
d = displacement;
v = velocity;
m = mass;
a = acceleration.

LW Sargent (1924), one of the first proponents of vertical jumping as a test of power, described his view of the theory behind it by stating:

> "the work done by causing the body to rise above the ground is the excess work done over that required merely to raise it from the squatting to the standing position, and this excess work consists of building up velocity, an accomplishment possible only when the rate of doing work (power) is above a certain minimum."
>
> (Sargent, 1924)

He devised the *Sargent jump*, a particular protocol for vertical jumping, and it became widely used over the decades (and is still being used today) as a measure of power. McCloy (1932) claimed that it was the best single measure for predicting 'explosive energy'.

Lightsey (1985) and Shetty and Etnyre (1989) suggest that to measure *leg power*, the vertical jump should *not* be started with a counter movement of the arms, because of the distinct contribution to jump height which the arms appear to make.

Power may not be a particularly useful term to use in analyzing many human performances, however, since it has generally been calculated as *average power* over various periods of time. For a given amount of work (the variable often measured along with time), the average power depends on the amount of time involved (i.e. the divisor). For example, 'aerobic power', 'anaerobic power', and 'explosive muscular power' are all normally calculated as average power over periods of time, and they are clearly dissimilar with respect to the amount of time involved, the total amount of work done, the underlying functional systems in operation, and the limiting factors in performance.

'Explosive muscular power', often also referred to as 'explosive strength', is used to describe work performed over a small (but still variable) range of time. And while these terms narrow power to a shorter time frame, it may still be an inadequate concept for describing the limiting factors involved in a vertical jump.

More recently, researchers have begun to question the use of the term 'power' to describe what is being measured by this jump. Adamson and Whitney (1971) describe power as being a carefully defined variable of applied mechanics, useful for assessing the working capacity of an engine or motor. They draw a distinction between 'power production' by an engine and 'power dissipation' into an external load or resistance. While in practical engineering applications production and dissipation can be seen as simultaneous, for impulsive actions such as jumping, power may not be a useful measure of muscular capacity. They state that the real measure of the action is the impulse (the integral of force with respect to time) that the coordinated muscle action can produce. This was shown above by equation 31, and is repeated here.

$$\Delta v = \frac{\int F dt}{m}$$

(Eq. 31)

In other words, the person with the largest power output (average or instantaneous) may not have the highest jump.

Further, they note that the instantaneous velocity of movement of the centre of mass in jumping is not due to the current force but to the preceeding force-time integral (that integral being the jumping impulse). The magnitude of the impulse will determine the take-off velocity for a given mass, and thus the height of the jump. They propose that the shape of the impulse curve may provide a good indicator of the muscular activity which caused it.

Adamson and Whitney (1971) give three theoretical approaches which different jumpers may exploit to increase the area of their impulse:

1. increasing the peak force;
2. increasing the impulse duration;
3. "squaring" the impulse curve - particularly by making the rising phase as steep as possible, (increasing dF/dt for t approaching 0).

Increasing the peak force and the impulse duration were discussed above, with respect to the difficulties small animals have with jumping, and the results of this study look at these factors as possible predictors. The squaring of the impulse curve as an optimal kinetic feature is also discussed by Dowling and Vamos (1993).

While this purely theoretical, technical perspective indicates that vertical jumping is *not* a measure of either average or instantaneous power, Dowling and Vamos (1993) empirically found peak power to be the best single predictor of vertical jump height (r = 0.93). Perrine et al. (1978) and Harman et al. (1990) have found similarly high correlations between peak power and vertical jump height (r = 0.85 to 0.92). The likely reason for this is described in the section on Kinetic and Temporal Factors (below, p. 85).

POSITIONAL STAGES OF A VERTICAL JUMP:

The initial kinematic studies on vertical jumping usually used position as a frame of reference for dividing the jump into its component parts (Hill, 1970; Kamon, 1971). Thus a jump consists of the following positional stages, as described by Miller (1976):

1. preparation - from the standing position to the lowest point in the take-off (now called the 'counter movement' (Asmussen and Bonde-Petersen, 1974a);
2. extension - the upward movement from the low point to the lift-off;
3. flight - the airborne phase;
4. landing - from contact to equilibrium.

KINETIC PHASES OF A VERTICAL JUMP:

Since the invention of the force platform, greater attention has been given to the assessment of the kinetics of the jump, and the measurement of the forces over time; specifically, the relative magnitude of the ground reaction force with respect to body weight. With this in mind, the jump can be divided into phases defined by kinetics, and the relative magnitude of the upward-directed *ground reaction force* (*GRF*) and the downward-directed *weight force* (*W*).

Miller (1976) divides the vertical jump into the following kinetic phases:

1. preliminary weighting and/or unweighting, which involves minor changes in *GRF* above and below *W*, and which may or may not be present;
2. major unweighting, which involves a definite reduction in *GRF* below *W* and a resulting negative (downward) acceleration of the centre of mass. If the jumper does not initiate any preliminary weighting, the major unweighting corresponds with the beginning of the downward motion. Desipres (1976) notes that the leg muscles contract eccentrically in this stage, doing negative work;
3. major weighting, during which *GRF* exceeds *W*. This begins while the jumper is still moving downward and continues until just before leaving the ground. At the beginning of this period, vertical acceleration is positive (upward), even though velocity is still negative, and the leg muscles continue to work eccentrically. The

maximal *GRF* normally occurs near the time that *v* has diminished to 0 and the jumper is at the lowest point. This is in accordance with generally accepted length-tension and force-velocity curves (see Chapman, 1985). *GRF* diminishes while velocity increases during the upward movement, which involves concentric contractions of the muscles and the production of positive work;

4. final unweighting, involving a very brief period just prior to take-off, in which *GRF* is less than *W*, and vertical acceleration is negative. According to Harman et al. (1990), this phase has a duration of 0.03 seconds, and results in velocity decreases of 6-7 %.
5. flight, during which the jumper's centre of mass follows a parabolic path, the acceleration (g) being a constant -9.81 ms^{-2}, and *GRF*=0;
6. landing, which involves a high impact force, *GRF*, followed by unweighting and fluctuations in *GRF* above and below *W* until the two are again equal.

These stages are illustrated in figure 2.3, below.

Fig. 2.3: SAMPLE COUNTER MOVEMENT JUMP IMPULSE PROFILE

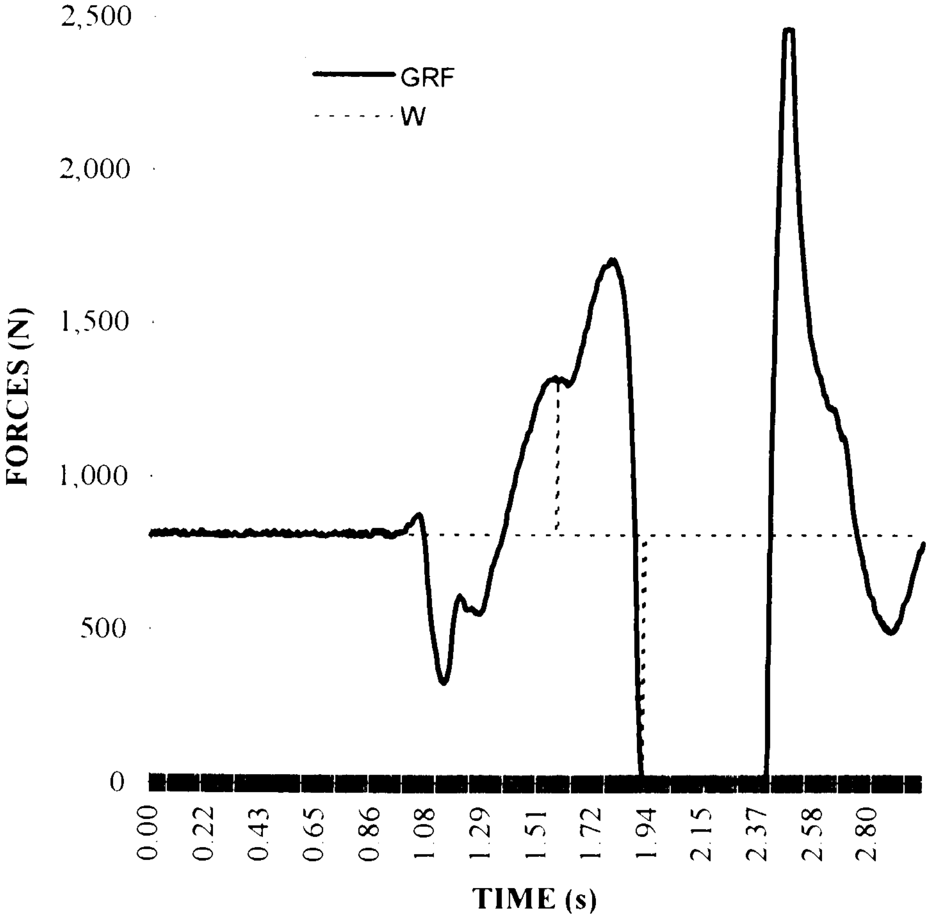

Fig. 2.3: Sample "Reach" jump impulse profile: male, 812.3 Newtons.

1	start of jump;
1 - 2	*preliminary weighting phase*;
2 - 4	*major unweighting phase*;
3	minimal countermovement *GRF* (e.g. 40% of W here);
4 - 7	*major weighting phase*;
6	peak (maximal) *GRF*;
7 - 8	*final unweighting phase*;
8 - 9	*flight phase*;
9 - 10	*landing*;

|Area B| minus Area A = Impulse Deficit;
Area C = Impulse Debt = Impulse Deficit,
Area D = Impulse Surplus;
Area D minus |Area E| = Jump Impulse.

Restating equation fourteen from above, it is the net upward impulse (after the downward impulse due to gravity acting on the jumper's mass has been subtracted), divided by body mass, that determines the velocity the jumper will have at take-off, and the height that will be achieved.

$$\frac{1}{m}\left(\int(GRF)dt-\int(W)dt\right)=V_{take-off}$$

(Eq. 35)

For the purposes of this study, the phases are described as defined by Miller (1976), although specific areas of the impulse profile have been assigned new names for convenience. They are shown in figure 2.3 (above), and are described below.

The major unweighting phase (point 2 to point 4), minus any preliminary weighting phase that may occur (point 1 to point 2), results in a *net* negative or downwards-directed impulse, and a negative (downwards) velocity in the countermovement. (The maximal negative velocity occurs at point 4.) The absolute value of this net negative impulse is herein called an *impulse deficit*, and is represented by area B (minus any positive impulse from area A, if it exists). The minimal countermovement force (point 3) occurs here, and in the example of figure 2.3, it is 40% of W.

In order to reduce this negative velocity to zero, GRF forces greater than W must be created to accelerate the jumper upwards. This upwards acceleration begins part way through the downward portion of the countermovement, from point 4, and by point 5 the net positive impulse has 'paid back' the impulse deficit. Area C is therefore a repayment period of *impulse debt*, which reduces the negative velocity to 0 at point 5, the bottom of the countermovement. The countermovement lasts from point 2 to point 5.

The extension stage begins at point 5. Area D is herein termed the *impulse surplus*, and it results in increased positive velocity from 0 at point 5 to maximal upwards velocity at point 7. The peak (or maximal) force usually occurs sometime during this period, and it of course represents the instant of greatest upwards acceleration.

The final unweighting phase occurs very briefly from point 7 to point 8, and it represents the necessary falling of the *GRF* from a value equal to *W* down to 0 at take-off. During this period acceleration is again negative, and upwards velocity is reduced slightly from its maximal value at point 7 to take-off at point 8. It should be noted that the faster a given subject's upward velocity is at point 7, the smaller area E will be and the less the reduction in take-off velocity. The *jump impulse* is area D minus the absolute value of area E.

The flight phase, or air time, occurs from point 8 to point 9, while the landing phase is shown from point 9 to point 10.

KINETIC AND TEMPORAL FACTORS:

Gerrish (1934) analyzed 270 jumps made by 45 Columbia University men, and found that while the height displacement varied within the narrow range of 1 to 2 feet (0.3 to 0.6 m), minimum counter movement forces varied from 15% - 74% of *W*, while the maximal forces ranged from 210% - 375%.

Miller and East (1976) found low intrasubject variability in the take-off velocities and kinetic patterns of their subjects' jumps. Desipres (1976) also noted that patterns of impulse in repeat performances were very similar for each individual, but differed significantly between subjects (e.g. the force dynagrams, or profiles, for his nonsportsmen appeared flatter, and lasted longer before take-off occurred, than for the athletes.) Dowling and Vamos (1993) reported a low within-subject coefficient of variation (standard deviation/mean) for take-off velocity in one subject (1.7 %) and a much higher intersubject coefficient of variation (14.7 %), and used this finding to justify having only one trial for each of the remaining subjects in their study. Harman et al. (1990) reported high test-retest reliabilities for the majority of the kinetic variables they obtained from four different types of jumps.

In comparing plotted averages of the five worst jumps versus the five best jumps, they found that large differences within each category obscured differences between the categories. Only very late in the take-off phase did the two shaded areas become markedly different, with the five worst jumps being characterized by a double peak of force in the positive impulse phase, compared to the five best jumps, which seemed to have only one. However, they failed to show a significant difference in jump height over-all between single-peak versus multi-peak jumps.

Oddsson (1989) and Jaric et al. (1989) also showed that a considerable amount of vertical jump performance variability can be explained by temporal, kinematic and kinetic variables. Oddsson (1989) obtained a multiple correlation coefficient of 0.86 between 10 force-time variables and vertical jump height, thereby explaining 73% of the jump height variance.

Perrine et al. (1978) found a good correlation between peak power and vertical jump height ($r = 0.85$). Similarly, Rosenstein et al. (1990) found peak power to be a better predictor of vertical jump height than was peak force ($r = 0.88$ and 0.49, respectively). Harman et al. (1990) added body weight to peak power and achieved a still higher correlation with jump height ($r = 0.92$).

Hochmuth (1984) advocated the use of kinetic and temporal information from force-time curves for the objective identification and optimization of athletic movements. Hochmuth and Marhold (1977) demonstrated, through the mathematical modelling of particle dynamics, the 'principle of late force development' (i.e. that peak forces, and therefore peak accelerations, occurring late in the movement were desireable for actions requiring a high final velocity (e.g. vertical jumping). This is difficult to achieve, however, since higher velocities of muscle shortening are associated with lower maximal forces (Chapman, 1985). Nonetheless, it is the requirement for relatively high forces at high velocities which likely results in the positive correlation between peak power ($F \cdot V$) and vertical jump height. This has led Hochmuth and Marhold (1977), Hochmuth (1984), Dowling and Vamos (1993), and others, to suggest that increasing strength is not enough to ensure improvements in activities such as a vertical jump, but that strength training should attempt to maximize the development of large forces at high velocities.

Harman et al. (1990) found peak positive power averaging over 3000 watts , and occurring about 0.07 seconds before take-off, shortly after the peak vertical *GRF* and just before the peak vertical velocity.

Garhammer and Gregor (1992) compared maximal and sub-maximal counter movement jumps, and found that subjects did not increase their performance by increasing the magnitude of force generation, but rather by increasing the rate of force generation and the duration of force at high percentages of maximum. They discuss the need for "U" shaped force-time curves as opposed to "V" shaped ones (their ordinate for force was inverted in comparison to figure 2.3 above), and thus they agree with Adamson and Whitney (1971) regarding the need to "square" the impulse curve. They also suggest that the neural learning of optimal motor unit recruitment patterns is required to achieve these "U" curves and resulting higher jumps.

In identifying the kinetic and temporal factors relating to vertical jump performances among ninety-seven young adults, Dowling and Vamos (1993) found that a high maximum force (> 2 body weights) was "necessary but not sufficient" (p. 95) for a good performance. In other words, while the best jumpers had characteristically high peak forces, some other subjects who produced high peak forces had relatively low jumps. Levine et al. (1983) and Zajak et al. (1984) have shown that forces greater than twice body weight can be generated by use of only the ankle plantar flexors in a vertical jump, obviously without great heights being achieved. Dowling and Vamos (1993) conclude that

> "The summed total torque-generating capacity of each joint, therefore, may not be as important as the continuity of the torque development and the ability to generate large torques late in the movement when the joints are nearing full extension and are rotating at high velocity."
>
> (Dowling and Vamos, 1993, p. 105).

This notion is supported by Jaric et al. (1989), who found that six lower extremity strength measures together only explained about 36% of the jump height variance.

The study by Dowling and Vamos (1993) showed that only seven of eighteen independent kinetic variables had significant ($p < 0.01$) correlations with the height jumped:

1. maximum force	(r = 0.519)
2. duration from maximum force to take-off	(r = -0.274)
3. maximum negative power	(r = -0.298)
4. maximum positive power	(r = 0.928)
5. duration from maximum positive power to take-off	(r = -0.406)
6. ratio of negative impulse to positive impulse	(r = -0.514)
7. maximum negative velocity	(r = -0.295)

All the variables explained considerably less than half the variance in jump height, with the exception of maximum positive power (r = 0.928) which explained over 80% of the variance. They pointed out that their higher correlations may have been due to the fact that their values were normalized to body weight. They concluded that

> "the large variability in the patterns of force application between the subjects made it difficult to identify important characteristics of a good performance."
>
> (Dowling and Vamos, 1993, p. 95),

and that

> "With the exception of the maximum positive power, many of the single-predictor variables that had triangular-shaped scattergrams seemed to require more information to improve the prediction of height."
>
> (Dowling and Vamos, 1993, p. 103).

Their best double predictor in multiple regressions was the combination of maximum force and the duration of the positive power phase, which explained 86% of the variance in jump height. They warn, though, that even if the explained variance is 100%,

> "interactions of the predictors in causing a good performance cloud the situation tremendously."
>
> (Dowling and Vamos, 1993, p. 106).

SEGMENTAL CONTRIBUTIONS:

Bangerter (1968) attempted to assess the contributive components in the vertical jump by randomly assigning subjects to specific 8-week strengthening programs. Significant gains in vertical jump height were found in the groups which strengthened knee and/or hip extensors, while no significant improvement occurred in the plantar flexor strengthening group. This led to the conclusion that the knee and hip extensors were much more important than the plantar flexors for this type of performance.

Payne et al. (1968) suggested that the arms added to the net upwards-directed impulse by superimposing a second peak on the vertical *GRF* force-time curves, changing what they claimed would otherwise be a smooth curve.

Miller and East (1976) attributed the two peaks largely to the trunk inertia force, and suggested that the upper limbs contributed merely by reducing the depression between these peaks.

Miller (1976) extended these findings and found consistent patterns with regard to segment contributions to the upward acceleration of the body in a small sample of college female subjects. During the major weighting phase, the absolute vertical acceleration of the trunk was almost always double peaked, dividing this phase of the take-off into two approximately equal parts. (This agreed with Miller and East (1976)).

The first maximum occurred coincident with the completion of the jumper's downward motion, and resulted mostly from the first eccentric and then later concentric contraction of trunk and thigh extensors. Relatively small contributions were made by the lower extremities during this first peak, although vertical acceleration of the hip with respect to the knee was also positive as thigh extension at the knee occurred. The acceleration of the lower extremities played the sole role in the second part, during the upward motion, with the thigh contributing a diminishing amount as the lower leg's contribution increased near take-off.

Of particular importance is her assertion that the trunk extension "is responsible for over half of the vertical impulse of the ground reaction force" (Miller, 1976, p. 363).

Luhtanen and Komi (1978) also used cinematographic and force-platform techniques in an analysis of separate segmental movements as well as complete vertical jumps. They reported that the take-off velocity of the complete jumps was caused by the different components as follows: hands 5%, forearms 8%, upper arms 9%, head and trunk 44%, thighs 16%, shanks 6% and feet 1%. This is in general agreement with Miller (1976). The individual segment performances contributed to a theoretical maximum take-off velocity as follows: knee extension 56%, plantar flexion 22%, trunk extension 10%, arm swing 10%, and head swing 2%. While this represents a quite different pattern, it appears unlikely that we can 'build' a predicted jump from individual segment performances with any great accuracy. The authors point out how changes in segmental timing and motor unit recruitment may change from individual segment performances to the total performance. It was also noted that the average take-off velocity of the total performance was only 76% of the theoretical maximum calculated from the segmental analyses. They suggested this as scope for improvement in skill and efficiency in jumping.

Robertson and Fleming (1987) used linked-segment analysis and inverse dynamics in analyzing the vertical jump, and reported the contributions to be as follows: hip muscles 40%, knee muscles 24.2%, and ankle muscles 35.8%. They also indicated that the sequence of contractions did *not* follow the proximal to distal pattern (see Luttgens and Wells, 1982, p. 421) assumed by the continuity principle, but that all three extensor moments acted simultaneously to produce the leg extensions.

In analyzing the coordination of segments in the vertical jump, Hudson (1986) had also found that the most representative pattern of coordination was simultaneous, and that for skilled jumping, the sequencing of segments (proximal to distal) was less important than the timing of segments (very small delays between adjacent segments).

Bobbert and Van Ingen Schenau (1988) argue that there is an optimal proximal-to-distal sequence of muscular activation which is as follows: the upper body, then the upper legs, the lower legs, and finally the feet.

Bobbert et al. (1986a and b) found the relative contributions for counter movement jumps to be the following: hips (38%), knees (32%), ankles (30%). This compared with Hubley and Wells (1983) who had calculated hips (28%), knees (49%), ankles (23%).

Pandy (1990) used optimal control theory to study vertical jumping, and modeled the human body as a four-segment, articulated, planar linkage. Quantitative comparisons between the model's predictions and experimental results obtained from several subjects indicated that the model successfully reproduced the major features of the real jumps. Pandy reported that a large proportion of the total energy delivered to the segments resides in the trunk, and that the combined energy of the thigh, shank and foot amounted to only 30% of the total energy made available at take-off. It was found that the vasti of the quadriceps and the gluteus maximus contributed approximately 90% of the total energy of the trunk, while the ankle plantar-flexors contributed significantly only during the final 20% of ground contact time. During this time, however, they accounted for about 30% of the total power delivered by the muscles to the trunk and up to 90% of the peak power delivered by the muscles to the thigh.

Jaric et al. (1989) found no relationship between dynamic leg strength and vertical jump performance. Genuario and Dolgener (1980) agreed, and found that isokinetically tested peak torques at high velocity were better related to jump performance than were those at low velocity. Neither were good predictors, however.

Perrine at al. (1978) found that peak isokinetic knee extension power was highly correlated (r=0.89) with vertical jump performance. Viitasalo and Aura (1984) agreed, and further suggested that training with high eccentric and/or concentric loads alone does not improve jump height. Thay suggested that training must involve the stretch-shortening cycle, and that the *rate* of isometric force development may be more important than the *amount* of the force. Bell and Jacobs (1986) and Jaric et al. (1989) found little relationship between the maximal amount of force and the rate of force development.

THE COUNTER MOVEMENT EFFECT:

While it is possible to begin a jump from a stationary position in a crouch and extend straight upwards (a static jump), most people seem to prefer starting from a standing position and preceding the upwards extension stage with a quick drop into, and directly out of, a crouch position (i.e. a counter movement jump).

Among others, Cavagna et al. (1968), Cavagna et al. (1971), Asmussen and Bonde-Petersen (1974a and b), Bosco and Komi (1979a), and Sanders et al. (1993), have found that jumps resulting from a 'stretch-shortening' cycle (more specifically, an eccentric contraction followed immediately by a concentric one) are greater than those produced by concentric-only contractions. Thus in vertical jumping, the positive work done by take-off, and the kinetic energy at take-off, appears to be greater in jumps that have a preparatory counter movement than in those that do not.

Tveit (1976) studied 320 children from different Norwegian schools, and found fairly equal results with regard to vertical forces. However, he found that the horizontal forces and impulses were smaller in take-offs with a preparatory counter movement than in those without one. This finding gave support to Hochmuth's assertion (1967) that muscular coordination is improved when the movement is started with a counter movement, and inefficient horizontal forces are then minimized.

Enoka (1988) reported a 12% jump height advantage with a counter movement among a group of forty-four subjects. Harman et al. (1990) also found that significantly greater heights were so achieved, as did Sanders et al. (1993).

There has been considerable attention given to attempting to explain the mechanisms involved in producing the greater vertical forces that are usually observed when a jump is preceded by a counter movement. Asmussen and Bonde-Petersen (1974a), Komi and Bosco (1978a and b), Bosco and Komi (1979a), Bosco et al. (1981), and Bosco et al. (1982a, b, and c) refer to the storage of elastic energy which results from the counter movement flexions and the stretch-shortening cycle. They suggest that utilization of the stored energy depends on the velocity of stretch, so that with increasing stretch loads the performance of the muscles improves, up to a critical point at which very high stretch loads will diminish the performance (Komi, 1983).

Asmussen and Sorensen (1971) and Cavagna et al. (1975) also noted that concentric work which immediately followed eccentric contraction was greater than that performed without prior tension development. Chapman (1985) considers that

> "These findings may be interpreted as being due to the storage of potential energy in the SEC (series elastic component) by the greater forces applied to it during eccentric contraction."
>
> (Chapman, 1985, p. 460)

Van Ingen Schenau (1984) provided an alternative hypothesis, suggesting that any increase in performance in counter movement jumps relative to static (squat) jumps is related to the fact that time is required to attain large forces in static jumps, whereas in counter movement jumps there is a large force already developed at the commencement of concentric contraction.

Chapman (1985), in a comprehensive review of the mechanical properties of human muscle, summarizes the research on a number of factors which appear to modify the force produced by the contractile component (CC), and suggests the order of importance as being:

> 1. its degree of activation;
> 2. its velocity of shortening;
> 3. its instantaneous length;
> 4. its immediate history of events (e.g. having been stretched).
>
> (Chapman, 1985, p. 461)

He notes that while takeoff velocity in vertical jumps is generally increased by the prior stretch in a counter movement,

> "---stretch may induce reflex effects which increase subsequent fiber recruitment, and the presence of series elasticity will modify CC (contractile component) velocity which in itself will change force output favorably in some circumstances."
>
> (Chapman, 1985, p. 455)

Chapman suggests that it is unlikely that the storage of elastic energy in the series elastic component (SEC) can account for most of the improvement seen in counter-movement jumps, because the SEC of the jumping muscles is not elastic enough to store significant amounts of energy. Even if it were, the CC would then shorten with too great a velocity, and reduced CC-generated forces and impulse would result.

In fact, he suggests that increased 'stiffness' of an individual's series elastic component may reduce contractile component velocity and thereby *increase* the generation of force, according to the general pattern of the 'family' of force-velocity curves (Chapman, 1985, p. 450). Furthermore, Chapman states that "the stiffness of the SEC varies among muscles of the same and different species" (1985, p. 458). It may be, then, that some people will gain more from a counter movement than others, based on 'stiffness' differences.

The role of the counter movement may be to allow the muscle enough time to reach maximum activation at the joint angles that allow the greatest torque and at a more favourable velocity for force generation (Chapman and Sanderson, 1990). This may be facilitated by reflex activation (e.g. the myotatic 'stretch' reflex resulting from muscle spindle activation). Further, force-velocity curves for muscle suggest that there is likely to be a much higher level of activation during the eccentric contractions of a counter movement than when no counter movement is present (Chapman, 1985; Mashima, 1984). Cavagna et al. (1968) showed how a toad's thigh muscle developed greater forces when being stimulated while being stretched, and Alexander (1992) states:

> "the areas under the (force-length) curves in this and in other similar experiments show that fast pre-stretching generally increases the work done in a subsequent shortening by about 50%."
>
> (Alexander, 1992, page 90.)

However, Chapman et al. (1985) have shown experimentally that large amounts of eccentric work appear to be no better than small amounts in increasing concentric work.

Chapman (1985) states that there is a

> "--- more rapid rise in force (that) follows quick release of an active muscle than when muscle is activated from rest."
>
> (Chapman, 1985, p. 452)

He concludes that muscle stretch (as in a counter movement) is performed to allow time for activation to rise (i.e. before the concentric phase begins), and that greater concentric impulses are subsequently produced because they have started at a higher force level above *W*.

While integrated EMG amplitude has been shown to be no greater during vertical jumps with a counter movement than during those without one (Bosco and Viitasalo, 1982), it can clearly be seen from figure 2.3 (above) that the forces required to reduce the downwards velocity of the countermovement increase the *GRF* to well above *W* at the start of the concentric extension phase (point 5 in figure 2.3, p. 87). In a static jump, the *GRF* and *W* are in equilibrium (by definition).

Hochmuth (1984) points out that the higher initial forces (at the start of the extension phase) that result from the braking thrust in a counter movement, result in a greater acceleration at the beginning of the extension phase. The distance available for extension may then be covered in a shorter period of time, thus limiting the time available for net positive impulse. In other words, a counter movement provides a substantial impulse advantage, only some of which is ultimately lost due to the increased velocity which this greater initial impulse has caused. On the basis of a series of test jumps, Hochmuth recommends that the braking thrust should be about one third of the acceleration thrust. He appears to be using 'breaking thrust' to refer to the net positive impulse which decelerates the downward velocity in the counter movement to zero (i.e. herein termed the *impulse debt*). The 'acceleration thrust' is therefore the net positive impulse from zero velocity to maximum upward velocity (i.e. herein termed the *impulse surplus*). In other words, Hochmuth suggests that in an optimal force-time curve, the impulse debt should be about one third of the impulse surplus.

Sanders and Wilson (1992) acknowledged generally larger forces at the beginning of the extension phase in counter movement jumps, but suggested that this may only have a minimal effect on performance since the centre of mass moves very slowly at the beginning, and the differences in work performed between static and counter movement jumps at this point are small. Sanders et al. (1993) found that *peak* forces were also generally greater in counter movement jumps than static jumps, although increasing the movement amplitude tended to decrease these peak forces.

Sanders and Wilson (1992), along with Hochmuth and Marhold (1978) and Hochmu (1984), stress the importance of having large forces during the period of high upwards velocity late in the major weighting phase of the jump. High forces during high velocities mean large power outputs (see equation 32, page 66).

Discussion above focussed on the advantage that larger animals have with respect to greater potential movement amplitudes, and the theoretical, potential advantage that taller humans may have over shorter ones for the same reason (assuming no difference in average force/mass ratios). Theoretically, one method that a shorter person could use to equalize this difference would be to increase the movement amplitude by initiating the extension phase from a lower position. This would involve starting from a lower position in a static jump, or dropping further in a counter movement jump. The possibility of a greater movement amplitude could theoretically explain any difference in results for static versus counter movement jumps. However, Bosco and Komi (1981) found that larger displacements of this type may actually result in a reduction in force.

A number of studies have shown a poor correlation between net negative impulse and the height jumped, even though a counter movement has generally been found to cause significant improvements in performance (Asmussen and Bonde-Petersen, 1974a and b; Bedi et al., 1987; Bosco et al. 1982; Komi and Bosco, 1978a).

Bosco et al. (1982) suggest that individuals with predominantly fast twitch muscle fibres are better able to recover stored elastic energy in high speed counter movement jumps with less knee angular displacement, while predominantly slow-twitch individuals may be able to recover more stored elastic energy in slower jumps involving greater knee angular displacement.

Dowling and Vamos (1993) showed that the ratio of negative impulse to positive impulse in a counter movement jump had a negative correlation with jump height (i.e., proportionally larger amounts of negative impulse in the ratio resulted in lower jumps). However, since counter movement jumps have typically been found to produce greater height, then having too little negative impulse in the ratio may also detract from jump height. They proposed an inverted-U relationship (which would lower a linear correlation value!) in a scattergram with jump height as the ordinate and the negative impulse/positive impulse ratio as the abscissa. They further suggested that an optimal ratio may be about 0.27.

Avis et al. (1986) found little advantage from the counter movement, in that only 4% more work was performed in the subsequent extension stage. They also found no positive correlation between the negative work done in the counter movement and the difference in positive work in the extension stage, and they suggested that elastic energy may be responsible for only a small increase in performance. However, they used only one movement amplitude (the distance moved during the concentric phase) in their testing.

Many comparisons of static and counter movement jumps have constrained subjects to preset movement amplitudes (e.g. Bosco and Komi, 1979a and b; Bosco et al., 1981; Hubley and Wells, 1983). Sanders and Wilson (1992) compared static and counter movement jumps of unconstrained movement amplitude. They felt that subjects should not be constrained to preset movement amplitudes, since that may upset the coordinated timing of the jumps and diminish any potentiation that might occur from the concerted action of the contractile and elastic components of the system.

In comparing the kinetics of static and counter movement jumps among eleven male and six female subjects, they had mixed results. Seven subjects achieved greater peak kinetic energy in the counter movement jumps than in the static jumps, mostly due to the increased forces. For two of the subjects, the difference was largely due to greater movement amplitude. Six subjects showed little difference in performance between the two types of jumps, while four achieved greater peak kinetic energy in the static jumps. Among the latter four subjects, three used a greater movement amplitude to achieve the greater kinetic energy in the static jump, while one actually achieved larger forces.

They were in agreement with Bosco and Komi (1981), by stating that there tended to be a trade-off between movement amplitude and the magnitude of the forces; such that if the movement amplitude was increased, peak forces tended to decline. The fact that this occurred in both static and counter movement jumps suggested that the phenomenon was not related to the storage of elastic energy from a counter movement. Sanders and Wilson could find little support for their hypothesis that subjects will achieve similar performance in static jumps (compared to counter movement jumps) by increasing movement amplitude in order to compensate for the slower buildup of forces. They further suggested that the best movement amplitude is likely to vary considerably among subjects, and that individuals may not naturally use the movement amplitude that maximizes performance.

They also suggest that counter movement jumps may benefit from a different pattern of ground reaction forces, rather than from the re-use of elastic (stored) energy. They note that the magnitude of the *GRF* at any particular moment is dependent on many factors, and that force production at each joint alters as the angle of that joint changes.

In a follow-up study, Sanders et al. (1993) hypothesized that since static jumps are likely to be less frequently encountered in the real world than counter movement jumps (and thus less practised), it may be that subjects performing static jumps have not learned to use the optimal movement amplitude, and that this may explain any advantage found with the counter movement jumps. However, in testing subjects over a 45 degree range of knee angles, they found that all subjects tended to achieve significantly greater kinetic energy at take-off in counter movement jumps than in static jumps.

Sanders et al. (1993) suggest that counter movement jumps may benefit from the freedom the subjects have to co-ordinate their segmental movements in ways which will maximize performance. Fukashiro and Komi (1987) found greater work performed by the muscles of the hip joint in counter movement jumps, whereas the muscles moving the knee and ankle performed similar work in static and counter movement jumps.

While determination of the exact mechanisms benefitting counter movement jumps is not the focus of this research, a general understanding of the potential factors involved was considered important for discussing potential relationships among the anthropometric variables and the kinetic characteristics of the vertical jump impulse profiles.

ARM SWINGS:

Payne et al. (1968) found the arm swing produced a 5% increase in jump height, suggested it caused a second peak in force during the positive impulse phase, and pointed out that it also ensured that the centre of mass was as high as possible before flight began (about 12% higher with arms than without). This latter point would only be an advantage if the absolute height obtained by the centre of mass was important, however. Also, a lower starting point noted for the jump without arms may have been a confounding factor.

Ramey (1973) found average increases in maximum force generation from 2.5 times body weight (when arm movement was not employed) to 3.7 times body weight (when arm movement was unrestricted). His estimate was that the arm swing contributed approximately 30 to 40% of the height of the jump.

Shetty and Etnyre (1989) found that the arms swings contributed to maximum force (6%), work done (14%), power (15%), and take-off velocity (6%). (They also found that the arms seemed to be used to reduce peak forces on landing by 12%!).

Compared with unskilled subjects, Coutts (1976) found greater increases with arm swings among volleyball players, as did Perrine et al. (1978) with basketball players. This suggests that these athletes may have learned how to use their arms more effectively.

Dowling and Vamos (1993) had their subjects use an arm swing, but 54 of the 97 subjects had only a single peak of force during the positive impulse phase. Miller (1976) found that the second peak was due to trunk acceleration, and that the arm swing merely reduced the depression between the two peaks.

Using only one body part at a time on a force platform, Luhtanen and Komi (1978) found that the arms contributed 10% to the take-off velocity. Harman et al. (1990), in a force platform study using both static and counter movement jumps, each with and without the use of the arm swings, also found the arms contributed a mean of 10% to take-off velocity for both counter movement and no-counter movement conditions. They also found that while counter movements and arms swings both improved jump height, the effect of the arm swing was greater.

From a theoretical perspective, three possibilities appear to exist:

1. the upswinging arms may simply transfer momentum to the rest of the body near take-off.
2. the arm swing may increase the downward load on the legs in the stretch phase of the stretch-shortening cycle (as suggested by Khalid et al., 1989) and thus produce increased activation;
3. Harman et al (1990) suggest that the upward acceleration of the arms creates a downward reaction force on the shoulders and the rest of the body. This slows the rise of the rest of the body, and also slows the contraction velocity of the hip and knee extensors. It may therefore take advantage of the force-velocity relationships of muscle by delaying the increased velocity of shortening (allowing higher force generation), as well as lengthening the time of force application. Both would enhance the impulse generated by the lower extremities while they are in a mechanically advantageous position. (They suggest that many sport activities may involve accelerating body parts not directly exerting force on the ground in order to slow down the contraction of the muscles most directly involved with external force application; this is consistent with Chapman (1985) and Chapman and Sanderson (1990).)

MUSCLE FIBRE TYPE AND VERTICAL JUMPS:

It has also been shown that a greater proportion of fast twitch fibres within a muscle will enhance both force production and the maximal intrinsic velocity of shortening (Forsberg et al., 1976; Woittiez, Huijing et al., 1985). Whether these individuals would gain more from the greater activation of a counter-movement is unclear, but it is likely that they would be able to perform both types of jumps better than individuals with a greater proportion of slow-twitch fibres in the same muscles. Since it has not been shown that anthropometric variables have any relationship to fast-twitch fibre proportions, this variable may well increase the error of predicting vertical jumps from anthropometry.

PSYCHOLOGICAL/MOTIVATIONAL FACTORS:

The levels of motivation and arousal (activation) of the jumper, the aggressiveness, the ability to concentrate and focus energy on the task at hand, and the ability to maximize motor recruitment and frequency of neuron firing, as well as minimize inhibitory mechanisms, may all play a contributing role in the vertical jump performance.

WARM-UP AND FATIGUE EFFECTS:

Pacheco (1957) studied the effectiveness of several types of warm-up exercises in the performance of five or more groups of six trials of standardized vertical jumping, and found that deep knee bends improved performance by 2.88%, isometric stretching by 4.99% and stationary running by 7.80%. Without exception, the mean performance of each subject was inferior in the absence of preliminary exercise.

Pacheco (1959) followed this up by studying running in place as the preliminary exercise before using the jump-reach test as the dependent variable. Her experimental design allowed her to separate warm-up and practice effects, both of which were clearly evident. Richards (1968) controlled for practice effects and found that 1 or 2 minutes of warm-up improved performance in a six-trial vertical jump test by approximately 20%, while 4 minutes had no effect and 6 minutes impaired performance by 27%. Those results agreed with an a priori mathematical model that predicted a slow but large exponential fatigue effect, and a faster but smaller exponential warm-up effect that improved performance. The difference between these two factors was the net improvement from the warm-up.

McCloy (1932) and Van Dalen (1940) both expressed concerns about adequate practice being given before the test. Neither established criteria for this, however. Bovard and Cozens (1928) had standardized the practice period at three jumps in one phase of their study, but they did not quantify the practice effects. Henry (1942) suggested three potential methods for standardizing practice:

1. All subjects are given a uniform amount of practice. But if subjects vary in performance improvement rates, scores may still be affected by inadequate learning.
2. All subjects can be given practice until some standard amount of improvement occurs.
3. Individual 'learning curves' (i.e. performance improvement curves) can be monitored continuously until learning has been completed.

In an experiment to test the best approach, Henry (1942) arranged repeated trials in pairs, with a 3-minute rest between the pairs and a 1/2 minute rest within each pair. He found that there was a consistent rise in performance level (i.e. a practice effect) up to the sixth trial, which showed a drop-off (i.e a fatigue effect). From that point on the odd tests (after the 3-minute rest) showed relatively higher jumps than the even tests 30 seconds later. The highest jump was at trial seven, with the odd-numbered jumps declining from that point on, giving evidence of a cumulative fatigue. Using the first trial as a reference, he calculates that there is an 87% chance that mean performances in trial three is higher, a 98% chance that trial five is higher, and a 99.9% chance that trial seven is higher. However, it was shown that individual differences in the amount of learning are small compared with individual differences in either the initial or the final test performances. As a result, Henry advocates the standardization of practice according to one of two options:

1. allowing all subjects a uniform practice series of three trials before the test series, or;
2. allowing no practice, and averaging the scores of five or more trials.

From elementary physics, we know that for any given angular velocity, a greater tangential velocity will occur at the end of a longer radius:

$$v_t = r\omega$$

(Eq. 36)

(Blatt, 1989, p 138)

where:

v_t = tangential velocity;
r = the radius;
ω = angular velocity (in radian units).

Similarly, for any given angular acceleration, a greater tangential acceleration will occur at the end of a longer radius:

$$a_t = r\alpha$$

(Eq. 37)

(Blatt, 1989, p 138)

where:

a_t = tangential acceleration;
r = the radius;
α = angular acceleration (in radian units).

As far as human jumping is concerned, the rise in the body's centre of mass occurs as a result of the summation of rotations at a number of different joints. With the foot fixed on the ground, the knees and hips extending and the ankles plantar-flexing, larger segmental lengths and greater resulting tangential velocities will produce a greater vertical velocity of the body's centre of mass, assuming the timing and magnitude of angular accelerations, and the final angular velocities, are held constant with increasing segmental lengths. Attaining greater stature, or more specifically greater lower extremity length, while holding everything else constant, would thus be an advantage. It would result in a longer-limbed jumper having a greater take-off velocity of the centre of mass than a shorter-limbed jumper whose average angular velocities are the same. However, this assumes that the longer limbed subject begins the positive work from the same angles of joint flexion, and that the same angular velocities can indeed be achieved.

Discussion on the allometry of jumping (p. 64 above) showed that the take-off velocity of jumping animals was dependent upon:

1. a *force mass ratio* $[L^2/L^3] = [L^{-1}]$;
2. a displacement through which acceleration can occur on the ground $[L^1]$.

It was stated that smaller animals, with shorter distances available for acceleration $[L^1]$, should theoretically be able to compensate by having larger 'force/mass' ratios $[L^{-1}]$, but that there are limits to this ability to compensate, since high muscular forces ultimately require greater skeletal mass (Bennet-Clark, 1977). The force/mass ratio thus has a 'ceiling effect' limitation, while the acceleration distance has no equivalent 'floor effect' limitation. Does this dilemma occur within the human species? Does the direct advantage of longer limbs offer a greater potential range for velocity improvement than the greater force/mass ratios are likely to provide among shorter-limbed humans?

The potential advantage to be gained by having longer lower extremities may be enhanced by the long-known observation that taller humans tend to be more ectomorphic (i.e. more linear) (Quetelet, 1833; Ross et al., 1987). Thus their force/mass ratios may not be as adversely affected by their increased size as might be expected by an *across-the-species* examination. (In fact, the increased linearity, and decreased *proportional mass*, with increased height within the human species is the very opposite of what we expect to find across the species, as animals tend to get proportionally more massive with increases in size along the mouse-to-elephant curve.) However, the increased ectomorphy found in taller people is also likely to be accompanied by a reduced proportional muscle mass.

Empirically, Viitasalo (1982) encountered an apparent length advantage in a comparison of Finnish and Russian elite male volleyball players, in which he found that the Russian players jumped higher in counter movement jumps on a force platform, and had longer lower extremities.

Ross et al. (1982b) compared female high jumpers from the 1976 Montreal Olympic Games to a group of Canadian reference females, and found that the high jumpers were proportionally short in sitting height (in other words, proportionally long in the lower extremities), and that the tibial length was also proportionally long. This supports the notion that there is an advantage to having long lower extremities and a larger crural index for jumping.

However, there is a need for some caution here. The criterion for success in high jumping is not specifically jump height, as defined here, but jump clearance. As Pennycuick (1992) points out:

> "A fence to contain antelopes needs to be 2 metres high, regardless of the size of the antelopes trying to jump over it. (However) The larger species may be able to clear a slightly higher obstacle, but that is because they start with their bellies further off the ground."
>
> (Pennycuick, 1992, p. 47).

Human high jumpers, especially those who make it to the Olympic Games, undoubtedly have excellent jump heights, as defined here (i.e. the maximal increase in vertical height of the centre of mass above where it was at the moment of take-off). However, their success also comes from the normally higher starting position of their centres of mass (they are usually tall), their ability to generate vertical impulse from a horizontal run-up, and their skill at wrapping themselves around the bar. There may be many others with just as good jump heights who could not do as well in the high jump event.

As Ross and Ward (1984) point out:

> "---in jumping to clear a particular object, or projecting body mass in single or multiple leaps, the higher the centre of gravity at take-off the better it is for the clearing or flight performance. Minimal 'excess' weight would also be an advantage. Thus, one might expect the elite jumper to be a tall, very linear individual."
>
> (Ross and Ward, 1984, p. 116).

Another anthropometric consideration has to do with non-functional (as far as vertical jump performance is concerned) 'dead-weight'. Large skinfolds represent greater subcutaneous adipose tissue, which has often been associated with a reduction in performance in explosive events such as dashes, jumps and short sprints (Cureton et al., 1975; Riendeau et al., 1958). Fleck et al. (1985) found that the U.S. National Women's Volleyball Team had a lower percent body fat (determined by hydrostatic weighing) than a U.S. Women's University Games Volleyball Team, and that their vertical jump height was significantly higher.

Increased adiposity has the potential to reduce vertical jump height in two ways:

1. It obviously adds to the overall body mass which must be accelerated upwards;
2. It probably adds to the moment of inertia around each proximal joint, thereby requiring greater torques to produce the same angular accelerations.

As Watson (1984) notes:

> "At body temperature the triglycerides of human adipose tissue are semi-liquid and would presumably act as a viscous constraint upon limb movement, an affect likely to be particularly pronounced when the velocity of movement is high. If this is the explanation, deposits located over rapidly moving muscles and joints would be expected to have a more pronounced effect upon the velocity of movement than trunk fat which merely increases body mass."
>
> (Watson, 1984, p. 202)

In assessing the effects of specific skinfolds on a field test of vertical jump performance, Watson reported that a maximum of 33.5% of the variance in vertical jump scores could be accounted for by seventeen skinfold measurements. Most of that variance was explained by the triceps, front and rear thigh, and calf skinfolds, and the addition of other sites had no significant effect. Watson summarized:

> "...the multiple regression analysis of the effects of individual skinfolds (on vertical jump) suggests that the "dead weight" effect is small when compared to the influence of fat located over the muscles which actually provide propulsion. It thus seems that the thickness of specific skinfolds may have a more important effect upon performance in certain explosive activities than does over-all body fat."
>
> (Watson, 1984, p. 202)

Greater lengths for acceleration and reduced adiposity 'dead weight' should of course be further benefitted by having greater associated muscularity for force production (i.e. strength), and, in keeping with the descriptions of animals (see the section on "Extremity and Segment Shape" starting on page 38 above), by having that muscularity concentrated nearer the hip, thereby reducing moments of inertia.

Many studies have shown generally positive but weak correlations between strength and various types of jumping ability. For example, Bale et al. (1984) studied 160 male university students enrolled in a fitness concepts class. They determined vertical jump height using a jump and reach technique according to the procedure outlined by Clarke (1967, p. 204), in which the height of the jumps was assessed by calculating the difference (to the nearest cm) between the subject's standing reach height and maximal jump reach height. They found that the heights (mean = 54.9 cm, s.d. = 8.50 cm) were similar to those measured on male athletes by Beckenholdt and Mayhew (1983). However, the correlation between isometric strength (measured by dynamometers) and vertical jump height was very low (i.e. in the range of 0.09 to 0.15). They stated:

> "The vertical jump scores showed very little relationship with any of the other strength measures, supporting the view that this test measures a different type of strength - explosive strength."
>
> (Bale et al.,1984, p. 3)

Categorizing their subjects into somatotype classifications according to Heath and Carter (1967), they found that mesomorphs (n = 15) jumped highest; on average, more than two cm higher than the Balanced Central group (n = 85). Ectomorphs (n = 7) had lower jumps (2 cm less than the Balanced Central group), while the worst jumps came from the Endo-

Meso group (n = 53, height averaging 4.3 cm less than the Balanced Central group. The muscularity and lack of adiposity apparently benefitted the mesomorphs, while the endo-mesomorphs may have suffered from the increased mass of their adiposity.

Bale et al. noted that the average mass of the Endo-Meso group was considerably greater than that of any other group, and that to jump the same height as any other group they would have had to provide a much greater impulse. They state that

> "It is therefore conceivable that the subjects in the endo-meso group display greater explosive strength without achieving the same height."
>
> (Bale et al., 1984, p. 5)

Indeed, when they converted the vertical jump heights to power output by taking body weight into account, using the Lewis Nomogram (see Fox and Mathews, 1981, p. 619-621), they discovered that the Endo-Meso group actually achieved the highest power output scores.

In a follow-up study on women students, Bale et al. (1985) found that they had significantly lower mean scores than the men for height, weight, and mesomorphy, and significantly higher skinfold measurements, percent fat, and endomorphy ratings. No significant differences in vertical jump height were found among the somatotype categories for the women, however, unlike for the men. They summarized:

> "Correlations among physique, strength, and performance variables were low, suggesting that physique did not have a marked effect on strength and performance."
>
> (Bale et al., 1985, p. 103)

Podolsky et al. (1990) found significant positive correlations between a number of strength parameters and the jump heights of eight female and ten male elite junior figure skaters performing axel and double axel jumps. Since strength is acknowledged to be proportional to the cross-sectional area of muscle mass (e.g. Alexander and Vernon, 1975; Alexander et al., 1981; Ikai and Fukunaga, 1968 and 1970), it seems logical to assume that muscle girth (circumference) measurements may also be correlated with jump height.

Cumming et al. (1973) determined anteroposterior calf muscle width from radiographs on 103 boys and 168 girls, all aged 13 to 16 years, and found a significant positive correlation with long jump among the boys ($r = 0.31$, $p < 0.05$), but not among the girls. Vertical jump was not measured. In looking at the relationship of calf muscle width to a number of other physical tests, they state that "leg muscle bulk is associated with a high exercise capacity and better sports performance" (Cumming et al., 1973, p. 93).

Ross et al. (1982b) found the female high jumpers from the 1976 Montreal Olympics to be proportionally smaller in all girths, skinfolds, and proportional weight. As was discussed above, to have small skinfolds is an obvious advantage, in that it minimizes the weight of tissues not related to the generation of upward impulse. While having proportionally smaller girths (especially in the lower extremities) may seem surprising, it is undoubtedly due to the fact that these women were tall more than they were muscular. The absolute value of their skinfold-adjusted girths may be just as large or larger than those of a reference group. It would be interesting to see their z-scores adjusted for mass instead of for height.

Girth measurements, as an estimate of local muscle cross-sectional area, should first be corrected for the amount of subcutaneous adipose tissue, usually by subtracting some index of a nearby skinfold measurement (see Drinkwater, 1984). Technically, since girths are linear measurements, the corrected girths should really then be squared in order to best represent muscle cross-sectional area and to remain dimensionally consistent with both area and force production. In practice, however, this is seldom done.

It must be admitted that a girth measurement is only a proportional estimate of muscle mass. Even after estimates of subcutaneous adipose tissue have been subtracted, there will likely be differences among muscles of identical size which will result in their having varying capacities for strength, power and endurance. There are many sources of potential variability which must be taken into account. For example:

- the proportion of fast twitch fibres within a muscle, which will enhance both force production and the maximal intrinsic velocity of shortening (see Forsberg et al., 1976; Komi and Bosco, 1978a; Woittiez, Huijing et al., 1985);

- the effects of myotatic reflex facilitation of contractile component force generation (see Awad and Kottke, 1964);

- the elastic, non-contractile capabilities of muscle (see Alexander and Bennet-Clark, 1977; Komi and Bosco, 1978a and b; Cavagna, 1977; Chapman, 1985; Chapman and Sanderson, 1990; Ettema and Huijing, 1990; Hudson, 1981 and 1985);

- effects of bi-articular muscles and geometrical constraints (see Gregoire et al., 1984; van Ingen Schenau et al., 1990; van Soest et al., 1992);

- the pennate structure and other muscle architecture (see Alexander and Vernon, 1975; Kaufman et al., 1989; Alexander and Ker, 1990);

- and the state of training and skill in relation to the jumps (see Ball et al., 1964; Berger, 1963; Blattner and Noble, 1979; Bosco and Pittera, 1982; Clutch et al., 1983; Dvir, 1985; Eisneman, 1978; Lesmes et al., 1978; McKethan and Mayhew, 1974; Miller and Power, 1981; Ono et al., 1976; Steben and Steben, 1981; Vergroesen et al., 1982; Viitasalo et al., 1981).

These non-macro-structural sources of variance may diminish individual prediction of force generation capacity from gross girth measurements. This does not deny the value of a structural orientation, especially when group data is concerned; it merely puts limits on the expectations we might have for *individual predictions* based solely on gross structure.

In summary, the following physics equation (Eq. 34, p. 69) was chosen to be the framework for the anthropometric modelling of the human vertical jump, since the literature suggests that anthropometric variables may be related to the equations component variables, especially if they are dimensionally scaled to be compatible.

$$h = \frac{\bar{F}d}{mg} \qquad \text{(Eq. 34)}$$

In addition to attempting to find standard anthropometric correlates and predictors of vertical jump performance, and to create predictive models for vertical jumping based on anthropometry, an attempt was made to answer the following questions, which developed from the above review of the literature:

Questions To Be Answered

1. Do stature and segment lengths correlate positively with vertical jump heights, by virtue of increasing the acceleration distance available, as is found across the biological 'mouse-to-elephant' curve?
2. Are appropriate muscle girths well enough correlated with force production that they may help predict vertical jump performance?
3. Is non-functional 'dead weight', in the form of subcutaneous adipose tissue, well enough negatively correlated with jump performance to improve its prediction?
4. Are body composition variables (particularly the estimates of percent muscle mass and percent adipose tissue mass) correlated with vertical jump performance?
5. Is muscle proximorphic shape related to vertical jump performance?
6. Is angularity of the lower extremities related to vertical jump performance?
7. Is the crural index correlated with vertical jump performance?
8. Are relationships between anthropometric and performance variables generally improved by being made dimensionally consistent?
9. Is a geometric or elastic similarity model most appropriate for assessing proportional differences within human subjects?
10. Can a unisex anthropometric model predict vertical jump without the need for the nominal description of gender?
11. Are the large average forces, required by the above physics equation, related to the peak forces occurring in the GRF force-time curve?
12. Do the peak forces relate to the anthropometric measures?
13. How is the net negative impulse (i.e. the 'impulse deficit') related to vertical jumps?
14. How is the impulse deficit/impulse surplus ratio related to vertical jump performance?
15. Is there a trade-off (i.e. a negative correlation) between peak forces and positive impulse time?
16. How well does 'air time' predict vertical jump performance?
17. Which adds more to a jump - an arm swing or a counter movement?

Chapter III

METHODS AND PROCEDURES

Section 1 - SUMMARY OF THE RESEARCH PURPOSE

The major purpose of the research was to enable the statistical prediction of the vertical rise of the centre of mass (CM) attained in three types of vertical jumps, from external macroscopic structure as measured by anthropometry. The three types of vertical jumps were as follows:

1. Static Jump: - a jump from an unconstrained static squat position, with the arms immobilized by keeping the hands on the hips;

2. Counter Movement Jump: - a jump initiated by an unconstrained counter movement, with the arms immobilized by keeping the hands on the hips;

3. Reach Jump: - a jump initiated by an unconstrained counter movement, with the arms freely swinging.

The modelling was theoretically based, and attempted to be explanatory as well as predictive. A secondary purpose was to examine certain characteristics of the force-time (impulse) curves that produced the jumps, and to see how these impulse profiles varied with respect to the structural variables. The independent (predictor) variables and the dependent (predicted) variables are summarized by table 3.1 below, and are described in more detail later in this chapter:

SUMMARY OF THE RESEARCH VARIABLES	
ANTHROPOMETRIC PREDICTORS	**PREDICTED JUMP PERFORMANCES**
measured structural variables	vertical rise in C M in 3 vertical jump types:
◆ size	1. (SJ) static jump (without use of arms)
derived structural variables	2. (CJ) counter movement jump (without use of arms)
◆ shape	3. (RJ) reach jump (with counter movement and arms)
◆ proportion	impulse profile characteristics in those jump types
◆ composition	

Table 3.1: Summary of the Research Variables.

Section 2 - DESIGN OF THE RESEARCH PROJECT

The research was cross-sectional and correlational in design, and consisted of two pilot studies and two formal studies. The pilot studies validated two new segment shape indices, and provided the researcher with experience in measuring vertical jump performances. The major laboratory study, which involved a force platform, was used to provide the data required to develop the predictive models. A field study done on professional hockey players, involving a portable force mat, produced data which was used to test the models. The study design is summarized in table 3.2 below.

RESEARCH DESIGN **Cross-sectional, correlational design**	
A. 2 pilot studies to validate new segment shape indices and gain vertical jump measurement experience	
B. **MAJOR STUDY** (LABORATORY: MODEL DEVELOPMENT)	**C.** **ICE HOCKEY STUDY** (FIELD: MODEL TESTING)
SUBJECTS: 100 subjects - 68 males, 32 females - comprised of 59 athletes (various sports), 41 university students	**SUBJECTS:** 68 male players - 21 Vancouver Canucks - 21 Milwaukie/Hamilton Admirals - 26 Seattle Thunderbirds & Juniors
INDEPENDENT (PREDICTOR) VARIABLES: *measured structural variables* - complete anthropometry (I.S.A.K. standards) - custom anthropometry (sequential girths) *derived structural variables*	**INDEPENDENT (PREDICTOR) VARIABLES:** *measured structural variables* - complete anthropometry (I.S.A.K. standards) - custom anthropometry (sequential girths) *derived structural variables*
DEPENDENT (PREDICTED) VARIABLES: *maximal jump from 3 trials of 3 types of jump* 1. Static vertical jump (without use of arms) 2. Counter movement jump (without use of arms) 3. Reach jump (with counter movement and arms) *impulse profile characteristics*	**DEPENDENT (PREDICTED) VARIABLES:** *maximal jump from 3 trials of 3 types of jump* 1. Static vertical jump (without use of arms) 2. Counter movement jump (without use of arms) 3. Reach jump (with counter movement and arms)

Table 3.2: The Research Design

Section 3 - THE ANTHROPOMETRIC DATA

Measured Structural Variables:

The anthropometry followed the standards of the International Society for the Advancement of Kinanthropometry (I.S.A.K.), and is described by Ross et al. (1982a); Ross et al. (1989); and Ross and Marfell-Jones (1990). There were 42 standard measurements made on each subject: weight, lengths, breadths, girths and skinfolds. The specific variables measured are listed by category in table 3.3 below.

LENGTHS	BREADTHS	GIRTHS	SKINFOLDS
stature	biacromial	head	triceps
sitting height	transverse chest	neck	subscapular
span	A-P chest	arm relaxed	biceps
upper arm	biiliocristal	arm flexed	iliac crest
forearm	humerus	forearm	supraspinale
hand	wrist	wrist	abdominal
thigh	hand	chest	front thigh
leg	femur	waist	medial calf
foot		gluteal	
spinale height		upper thigh	
trochanterion height		mid thigh	
tibiale laterale height		calf	
		ankle	

Table 3.3: Anthropometry by Category

Derived Structural Variables:

ROSS-WILSON PHANTOM PROPORTIONALITY Z-SCORES:

While the anthropometry directly measured size, these measurements were also used to estimate aspects of shape, proportion, and composition. Phantom proportionality Z-scores were used here to adjust the anthropometric values for total body mass, since mass was what was being accelerated upwards in the vertical jumps. The equation for the proportional, mass adjusted anthropometric values is:

$$z = \frac{1}{s}[v(\frac{64.58}{mass})^d - P]$$

(Eq. 38)

where:

v = the variable measured;
P = the designated phantom value for that variable;
s = the standard deviation from a hypothetical human population for variable v;
$(64.58/mass)$ = the scaling ratio in kg., i.e. the phantom mass constant over obtained mass;
d = a dimensional exponent producing dimensional consistency, (e.g. if v is stature, d, scaling for mass, is 1/3);
z = the proportionality value.

The general concept behind this method is discussed in Chapter II above. For more complete descriptions of this approach, see Ross and Wilson (1974); Ross (1978); Ross et al. (1980); Ross et al. (1984); Ross (1985); Ross et al. (1989); and Ross and Marfell-Jones (1990).

KERR FRACTIONAL TISSUE MASS ESTIMATES:

Fractional tissue mass estimates were made for bone, muscle, adipose tissue, skin, and residual masses, according to Kerr (1988). Again, anthropometric values were used as input, and an analysis was made of the percent error in predicting total mass from the tissue mass estimates (see chapter IV).

WEIGHT-ADJUSTED SUM OF (EIGHT) SKINFOLDS (SOS_w):

The sum of (eight) skinfolds (SOS) was also weight-adjusted, to give an overall proportional adiposity rating (SOS_w), according to the following equation:

$$SOS_w = SOS\,(64.58/mass)^{1/3} \qquad \text{(Eq. 39)}$$

where:

$(64.58/mass)^{1/3}$ = the scaling ratio for mass in kg.

HEATH-CARTER ANTHROPOMETRIC SOMATOTYPE:

Heath-Carter anthropometric somatotype ratings were calculated for endomorphy, mesomorphy and ectomorphy, according to Carter (1975). The sum of three skinfolds (triceps, subscapular, and supraspinale) were height adjusted to dissociate size in the endomorphy rating.

CRURAL INDEX:

The crural index was defined in Chapter II as the ratio of the shank (leg) length to the thigh length, with values greater than 1.00 indicating proportionally longer distal segments. This has been suggested (see Chapter II) as being an advantage for faster running and better jumping, among both animals and humans. However, since specific landmarks were not stated in the literature, a crural index was herein operationally defined.

$$\mathit{CRURAL\ INDEX} = \mathit{TIBIALE\ LATERALE\ HEIGHT} / \mathit{THIGH\ LENGTH} \tag{Eq. 40}$$

It should be noted that tibiale laterale height included the ankle and foot, since the tibial length itself, without the talus and calcaneus being included, was considerably less than that of the femur, and would have resulted in indices much less than the vicinity of 1.00 which is reported in the literature.

LOWER EXTREMITY MUSCLE PROXIMORPHY INDEX:

Ideally, a lower extremity muscle proximorphy index should take into account the powerful hip extensor muscles, particularly gluteus maximus. The gluteal girth should therefore be included. However, in humans, the gluteal girth measurement may include large masses of adiposity. This is likely to be particularly true with females, who may have large adipose sites on the lateral portion of the hip exactly where the gluteal girth is taken. Without an adjustment factor for adiposity in this area, large proximorphy indices could result from either muscularity or adiposity. Since many subjects may have objected to skinfold measurements being taken near the gluteal site, the mid-thigh girth was chosen instead.

The *muscle proximorphy index* for the lower extremity was operationally defined, for the purposes of this study, as being the skinfold-adjusted mid-thigh girth, minus the skinfold-adjusted calf girth. The difference was then height-adjusted to factor out size and make it an index of shape, as is shown below. While the vertical distance between the two girth sites would have been the ideal way to adjust the difference for size variance, this would have added yet another measurement to an already-long series of measurements. The Ross-Wilson phantom height-scaling approach was therefore used as a proxy.

$$PROXIMORPHY\ \ INDEX = (MID\text{-}THIGH\ GIRTH_C - CALF\ GIRTH_C)$$

$$X$$

$$(170.18\ cm \quad HEIGHT\ cm)$$

(Eq. 41)

The skinfold adjustment for the girths was made by subtracting π times the skinfold divided by 10 (since the skinfolds are measured in millimetres while the girths are in centimetres). The skinfold was multiplied by π under the common assumption that subcutaneous adiposity and the surrounded muscle and bone can be modelled as concentric truncated cones (see Drinkwater, 1984). The equation for the skinfold correction is shown below:

$$GTH_C = GTH - \left(\pi \bullet \frac{SF}{10}\right)$$

(Eq. 42)

Figure 3.1 (below) shows the measurements required for the lower extremity's muscle proximorphy index, as created for this study.

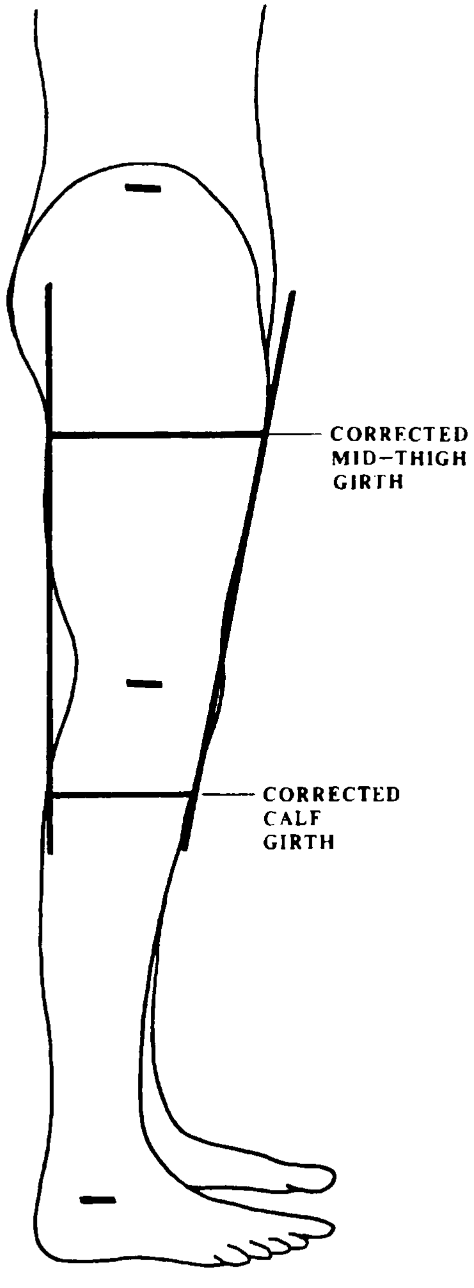

Figure 3.1: Measurements for the Proximorphy Index of the Lower Extremity:
The lateral bony landmarks (trochanterion, tibiale laterale, sphyrion laterale) that define the ends of the segments are shown; as are the two girths (mid-thigh and maximal calf) that determine the Proximorphy Index.

ANGULARITY INDEX:

Body-builders, who are high in both muscle mass and muscle definition, are often referred to as being 'cut' or 'chiselled'. It seems reasonable to assume that a silhouette of a body-builder would tend to show more 'lumps and bulges' than would one of a sedentary individual of the same sex, height and weight. The outline of the body builder would be likely to include greater amplitude in the changes of the angles which the outline formed. Measuring the angles themselves, and the changes they make in forming an outline, would be a tedious task. However, if a few girths were measured at standardized sites down a body segment, the change in those girths down the axial length of the segment (i.e. the first derivative of the girths with respect to the axial length of the segment) could provide a simple estimate of the *'angularity'* of the segment shape.

Accordingly, an *angularity index* was created as follows:

1. A segment was defined by the proximal and distal bony landmarks already required by standard anthropometry.
2. The segment was divided into 15 equal sections (based upon the findings of a pilot study), which with the section boundaries provided 16 equally spaced girth sites.
3. These girth sites were measured in the same way as are all other standard girths, with the tape being held perpendicular to the longitudinal axis of the segment.

4. To dissociate size effects from the shape index, the girth measurements were adjusted for segment length according to the following equation:

$$GIRTH_A = GIRTH \times (15 / SEGMENT\ LENGTH)$$

$$[L^0] = [L^1] \, ([L^0] / [L^1])$$

(Eq. 43)

5. The first differences of the length-adjusted girths were taken by subtracting each girth from the next most distal one. If the girths became larger, the difference scores were positive. If the girths got smaller, the difference scores were negative.
6. The girth differences were squared, summed, and divided by the number of girth differences. The square root of this (i.e. the *root mean square* of the length-adjusted girth differences) was the angularity index for that segment.

With this procedure, the angularity index of a perfect cylinder would be zero, and there would be no upper limit to the angularity index of an irregularly shaped object. It should be noted that a high angularity index simply means, herein, a deviation from a cylindrical *shape*, the way a cheetah's lower extremities appear to differ from those of an elephant. Assumptions of greater muscularity are not warranted without other information. For example, a very obese person may have as large an angularity index (or perhaps even larger) than that of a body builder. Measures of shape are not measures of composition!

Figure 3.2 (below) shows the 16 girth sites per segment for the lower extremity (i.e. 16 for the thigh, 16 for the shank). The first site for the thigh was the trochanterion landmark. The sixteenth site for the thigh was the same as the first site for the shank, and marked the boundary between the two segments (i.e. tibiale laterale).

It should also be noted that not all sites could be properly measured. The first three sites at the thigh embraced the trunk as a whole, and could not be used to derive an angularity index for the thigh. The fourth site could sometimes be measured, but often only by moving the anthropometric tape away from the required horizontal position. It was therefore not used. The last two girths on the shank surrounded the increasing mass of the foot, and if included, would have biased the angularity index away from the intention of *indirectly reflecting* (but not measuring) muscular development and definition. They, too, were not included.

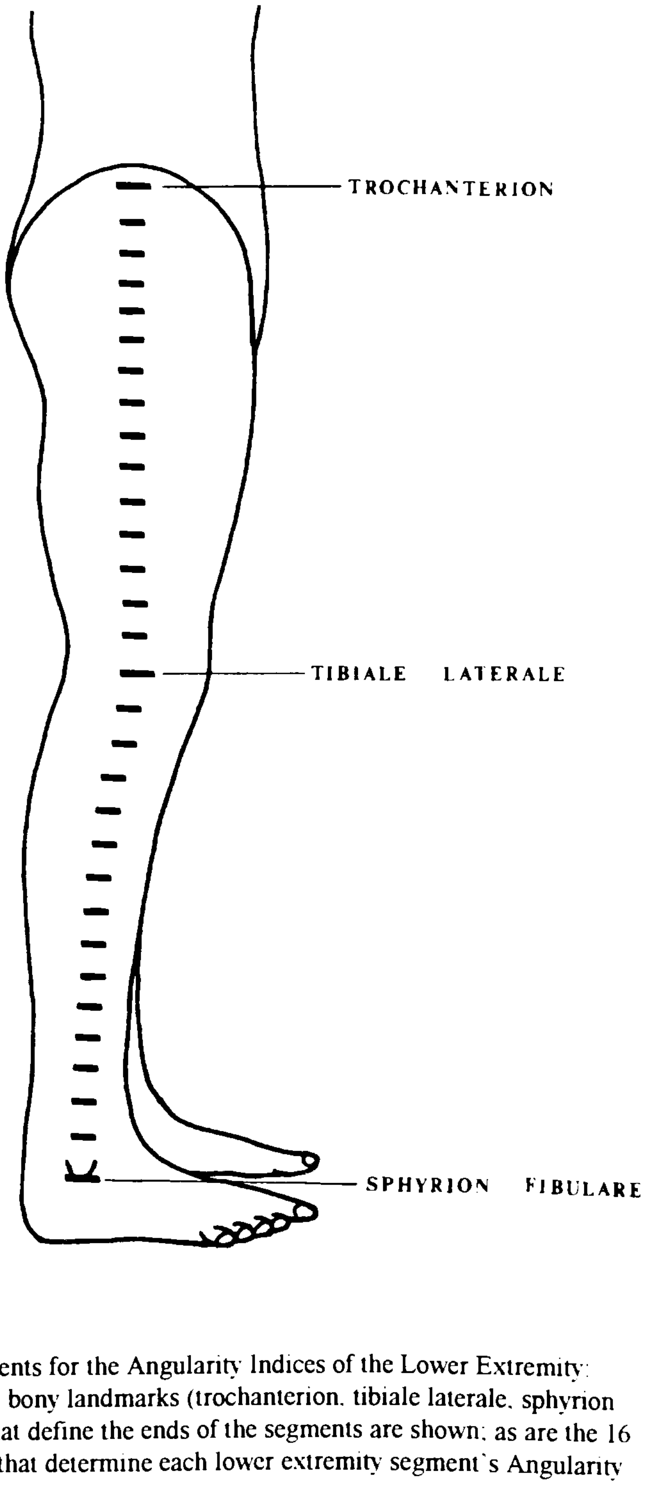

Figure 3.2: Measurements for the Angularity Indices of the Lower Extremity: The lateral bony landmarks (trochanterion, tibiale laterale, sphyrion laterale) that define the ends of the segments are shown; as are the 16 girth sites that determine each lower extremity segment's Angularity Index.

Section 4 - THE VERTICAL JUMP DATA

Force Platform Data (The Major Study):

The vertical jumps in the major study used a Kistler piezoelectric force platform (from Kristal Instrument Corp., Grand Island, New York) which was capable of measuring forces in three planes. It was connected to a Kiag Swiss Charge Amplifier (Type 5001), which transformed the charges from the force platform into proportional voltages. These were then downloaded to an IBM-compatible AT (80286) computer, running Labtech Notebook (version 6.0 with ICONview), from Laboratory Technologies Corp., Wilmington, Massachussetts. The analogue signals from the amplifier were converted by the Labtech Notebook A-to-D board into digital form, and stored on the hard drive by automatic saving routines. The setup module of the Labtech Notebook software was programmed to capture at a frequency of 200 Hertz for a three second period, with keyboard triggering. Two channels were used: one for automatic time recording in two-hundredths of a second, and one for vertical force capture (the z-axis). Forces on the other two axes were not captured, but were assumed to be minimal since the subjects were required to land on the force platform.

Force Mat Data (The Hockey Study):

The vertical jumps in the hockey study were performed on a portable Impax 420 Force Platform System (from Impulse Technology, Inc., Bay Village, Ohio). This portable unit is hereinafter referred to as a force mat, to differentiate it from the conventional force platform used in the major study. The unit consisted of a round, rubber platform, the perimeter side wall of which contained a very thin, acoustic-sensing piezoelectric film. Forces directed on to the platform generated a proportional shock wave which radiated outwards to the piezoelectric film sensor. The unit was *not* like a switch mat, which would only indicate the presence or absence of a load above a certain threshold, and would then simply calculate jump height from time in the air (see chapter II). The Impax 420 delivered analog feedback relating to both force and time over what was advertised to be a "broad dynamic range" of force. A battery-operated microprocessor with LCD readout provided visual display of the jump data.

While it was advertised as being able to calculate vertical jump height, ground time, ground reaction force, and coupling time (elapsed time from initial movement to take-off), only vertical jump height was recorded in this study.

Section 5 - SUBJECTS

The major study comprised 100 subjects, all of whom volunteered to participate. There were 68 males and 32 females. Among them, 59 were athletes in various sports at provincial, national or professional levels (except for the figure skaters, who were members of a community-based club). The athletes came from sports which included NHL hockey (8), speed skating (12), figure skating (9), cycling (9), track and field decathlon (13), track and field high jump (2), and weight lifting (6). The other 41 subjects were undergraduate and graduate students in the Kinesiology program at Simon Fraser University in Burnaby, BC, Canada. The students provided a reasonably healthy and fit reference sample, and most also participated in various sports - some at fairly high levels.

The nine figure skaters in the major study were treated separately in many of the following analyses, and ommitted from others, since they were generally much younger (mean age 12.0), and since pre-pubertal proportions are notably different from those of adults (see Ross et al. (1989); Tanner (1978); and Faulkner and Tanner (1986)).

The 68 hockey players were all males. They included 21 from the National Hockey League (Vancouver Canucks), 21 from the International Hockey League (Milwaukee Admirals), and 26 Juniors, primarily from the Seattle Thunderbirds. Their respective teams included this testing as part of their overall testing program for that year.

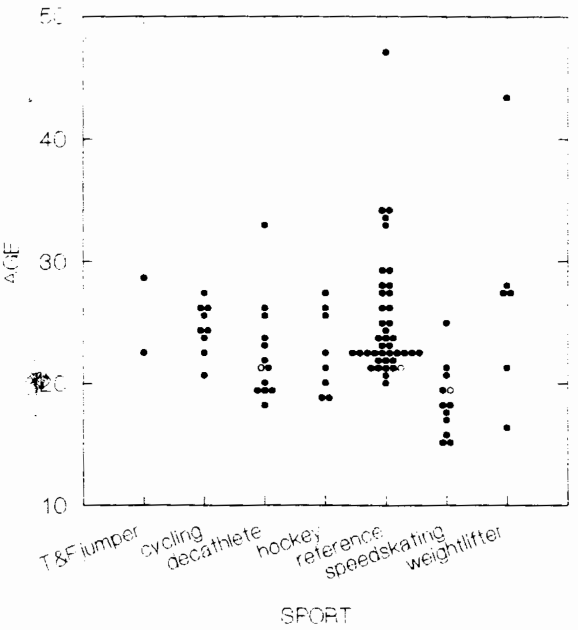

Fig. 3.3: Dot-Plot of Subject Ages in the Major Study.

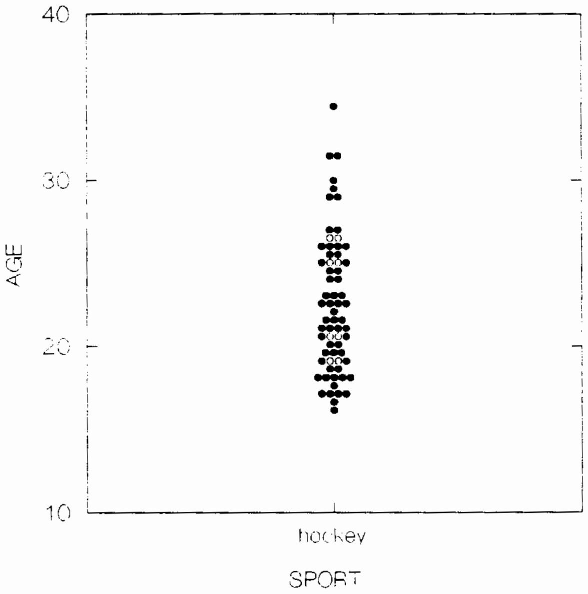

Fig. 3.4: Dot-Plot of Subject Ages in the Hockey Study.

The ages of the subjects are summarized in table 3.4 below.

AGES (Yrs.)	MAJOR STUDY	(Figure Skaters)	HOCKEY STUDY
Minimum	14.9	9.5	16.3
Maximum	46.9	17.5	34.4
Median	29.5	10.1	21.6
Mean	29.5	12.0	22.5
St. Dev.	5.1	5.7	4.1

Table 3.4: Ages of the Subjects.

Because the sample of 100 subjects in the major study was not randomly selected from either a general population or a stratified subgrouping of athletic or other populations, caution must be taken when attempting to generalize the findings of this study to any other sample or population. While this is a problem in most human studies (volunteers comprise a biased sample), it delimits this study in two ways. First of all, sedentary and overfat people were not included here, in order to ensure that all subjects had considerable movement and/or sport experience, and could focus their energy on "exploding" into a vertical jump. While this hopefully reduced non-structural variability in the performance of the vertical jumps, it also reduced structural variability by omitting subjects with large adiposity. The ability to generalize from this study is made somewhat narrower by this.

Second, these subjects cannot be said, with confidence, to be representatives of their sports, due to their small numbers per sport and the fact that they were volunteers.

Section 6 - DATA COLLECTION PROTOCOLS

The testing sessions lasted from 1 to 1$^1/_4$ hours per person, during which the anthropometry took 45-60 minutes and the jumping about 15 minutes. All subjects were first asked to read and sign informed consent forms. The anthropometry was taken next, with three measures made on each variable, except for weight, stature, sitting height, arm span, and the sequential lower extremity girths, for which only one measurement was sufficient due to their robust test-retest reliabilities. The median of the three measures for the other variables was used for modelling purposes. (If the first two measurements were the same, a third was not taken, since by definition the median had already been determined.). The jumping was tested last. This general protocol was maintained throughout both the major study and the hockey study.

It should be noted that the measurement of body weight in the major study was made very carefully, on a calibrated balance-beam scale, since subject weight was then used to calibrate the force platform while the subject was motionless. This is discussed in more detail in chapter IV.

Section 7 - JUMPING PROTOCOLS

Three types of vertical jumps were performed, with 3 repetitions of each, for a total of 9 jumps. The best jump of each type was chosen for modelling purposes. Approximately one minute of recovery was given between jumps, according to Shetty and Etnyre (1989). A series comprised three jumps - one of each type. There were three jump series for each subject. The three types of jump were as follows:

1. Static Jump (SJ):

This was performed from a motionless, unconstrained squat position. Subjects were given the general goal of ninety-degree flexion at the knees, but were not forced into an exact position (see Sanders and Wilson, 1992). Hands began on the hips and remained there throughout the jump (see Viitasalo, 1982). Static jumps were later eliminated if the GRF fell below 80% of W before peak force was obtained, since a drop below 80% was operationally defined as a counter movement jump.

2. Counter Movement Jump (CJ):

This was performed from a motionless standing position, and was initiated by an unconstrained counter movement. Subjects were given the general goal of descending to approximately a ninety-degree flexion at the knees in the counter movement, but were not limited to an exact range of motion (see Sanders and Wilson, 1992). Hands began on the hips and remained there throughout the jump (see Viitasalo, 1982). A jump which had a drop in the GRF below 80% of W before peak force was obtained, with hands remaining on the hips, was operationally defined as a counter movement jump.

3. Reach Jump (RJ):

This was performed according to the instructions for the counter movement jump, except that the arms were allowed to swing fully upwards during the extension phase. A jump which had a drop in the GRF below 80% of W before peak force was obtained, with arms freely swinging upwards, was operationally defined as a reach jump.

JUMP TYPE	JUMP DESCRIPTION
Static Jump (SJ)	- no counter movement (minimum GRF > 80% body weight) - no arm use (hands stay on hips) - jump begins from a squat position (about 90° at the knees)
Counter Movement Jump (CJ)	- unconstrained counter movement - no arm use (hands stay on hips) - jump begins from a standing upright position
Reach Jump (RJ)	- unconstrained counter movement - arms swing upwards to reach as high as possible - jump begins from a standing upright position

Table 3.5: Jump Type Descriptions

In order to reduce any potential bias from the order of jumps, the order was randomized according to a quasi-magic square designed by Dr. L. Weldon of Simon Fraser University. Three cards were made up with the name of one jump type on each card. Each subject drew two cards successively, and randomly, from the shuffled deck of three. The cards were drawn without replacement. This process established a random order for the first jump of each type (i.e. the first series), with the six possibilities shown in table 3.6 below:

1ST SERIES POSSIBLE ORDERS	1ST JUMP	2ND JUMP	3RD JUMP
1	SJ	CJ	RJ
2	SJ	RJ	CJ
3	CJ	SJ	RJ
4	CJ	RJ	SJ
5	RJ	SJ	CJ
6	RJ	CJ	SJ

Table 3.6: Possible Orders of First Series of Jumps.

Once the order within the first series was established, the order within the second and third series was fixed, according to Weldon's quasi-magic square, which equalized the weighting effect of the order determined by the first series. Table 3.7 (below) shows that all the jumps, numbered from 1 to 9, were ordered such that each jump type totalled 15. No matter which one of the six potential orders was chosen for the first series, each jump ended up with an *order weighting* totalling 15 after the three series were completed. The importance of this was to attempt to reduce any possible biasing effect that the order of the jumps may have had as a result of warm-up, practice, or fatigue factors, if they did exist. (Potential biasing in this regard is assessed in Chapter IV below.)

JUMP TYPE	1ST SERIES	2ND SERIES	3RD SERIES	ORDER WEIGHTING
A	1	5	9	15
B	2	6	7	15
C	3	4	8	15

Table 3.7: Weldon's Quasi-Magic Square for Equalizing Order Weightings

As an example, if the static jump occurred first in the first series (i.e. jump type A in table 3.7 above), it then occured again as the fifth and ninth jumps overall. The order weighting for that jump was then (1+5+9) = 15; the same as the order weighting for the other two jumps.

Section 8 - DATA PROCESSING

The anthropometric data and the portable force mat data were manually entered into Microsoft Excel for Windows, version 5.0; a module of the Microsoft Office for Windows software suite. Median values of the three repeat measurements were chosen for modelling purposes, while all three measures were used to determine the technical error of measurement, the percent technical error, and the reliability (see chapter IV). (Note: If the first two measurements were the same, a third was not taken. These identical measures were then not included in the error calculations.) The captured vertical jump force and time data were also imported to spreadsheets, and manipulated as explained in chapter IV.

Section 9 - DATA ANALYSIS

Anthropometric derivations, the quantification of the impulse profiles, and many of the descriptive statistics and charts were produced within the spreadsheets. Principal components analyses, multiple regressions, and some other specific statistical functions were performed by importing the spreadsheets into Systat for Windows, version 5.0 (a dedicated statistics software package for the DOS/Windows environment).

Section 10 - THE MODELLING APPROACH

It is this author's contention that any modelling process should begin with a clear statement of the orientation or perspective of the researcher, and the assumptions, delimitations and limitations that underlie the procedures followed. This may be particularly important when large amounts of data are gathered, as was the case herein.

Draper and Smith (1966) describe predictive modelling as the only type of multiple regression analysis that does not require a precise *a priori* knowledge of the true functional relationships between the dependent and predictor variables. However, prediction by itself was not enough in this case. An equation totally devoid of any theoretical validity may have boasted good predictions, but may have provided absolutely no explanation of the underlying functional relationships. A purely empirically-derived model that best predicts a given variable may be somewhat sample-specific (especially if proper tests are not done), and may well include non-causative *bystander* variables as predictors. Since most models are imperfect, some degree of wrongness in such a model may not eliminate its usefulness. However, without due caution, it may encourage faulty interpretation of the way in which the factors comprise the model, or it may distract the researcher from a more useful focus.

The numerous anthropometric variables, derived proportional indices, tissue estimates and shape coefficients included herein, are naturally likely to be much more highly related to each other than to any predicted performance variable. Multicolinearity is to be expected with such a large and comprehensive anthropometric data set. This may become a problem in multiple regression techniques if the large numbers of variables are, without *a prioiri* justification, put forward as potential predictors. While multiple predictors can be arranged to have a higher correlation with a dependent variable, the extent to which the predictor variables are colinear will cause the coefficients to have larger standard errors of prediction.

However, to avoid looking at the correlations that apparent bystander variables may have with the dependent variable increases the chance that valid but currently unknown relationships may not be discovered; i.e. the chance of a Type II, or beta, statistical error. A truly explanatory model is likely to occur most frequently when the process of modelling begins with a theoretical perspective, which is then refined and modified empirically, on the basis of accumulated data. There may therefore be a number of phases involved, each involving exploration and then confirmation, with theoretical relationships being modified and refined by empirical findings, and tested once again. The researcher must therefore walk a tightrope between the unwanted extremes of 'making the theories fit the data' versus 'throwing out valid theories because they do not explain everything about the data'.

The perspective taken in this research can be best summarized by the title (and content) of a book by C.J. Pennycuick (1992): "Newton Rules Biology: A Physical Approach to Biological Problems". In summarizing his own and others' research, he continually points out the physical limitations and constraints that shape biological diversity. Biology serves physics, and structure must obey long-understood physical principles.

With this in mind, the modelling process engaged herein was primarily theoretical in nature, and was based upon the concepts and equations reviewed in chapters I and II above. Predictor variables included in any final models were required to meet the criterion of making conceptual sense, and had to keep in mind the dimensional relationships established above.

Projects like this one, in which enormous amounts of data are gathered in a search for relationships, have sometimes been called 'fishing expeditions'. As such, one might be considered a fool to throw away a big catch just because it wasn't what was being fished. Nonetheless, unexpected catches must be carefully scrutinized for their meaning. The orientation herein contains a strong theoretical bias.

The equation that served as the basis for the theoretical modelling (equation 34, which was derived from equations 26 and 24 in Chapter II above) was the one which appeared best for producing an anthropometric analogue: (i.e. forces are roughly proportional to the cross-sectional area of muscle, while the distance available for the force application may be related to stature or segment lengths). The re-formatted equation and its dimensional characteristics are described below.

$$h = \bar{F} \times \frac{1}{m} \times d \times \frac{1}{g}$$

(Eq. 44)

and

$$h \propto [L^{2}]\,[L^{-3}]\,[L^{1}]\,[L^{0}]$$

$$h \; \alpha \; [L^{0}]$$

(Eq. 45)

The anthropometric analogue was constructed with these equations in mind, and with a number of potential or *candidate* variables within each category (see Table 3.8 below).

Effective Force Production		**Mass Accelerated**	**Work Distance**
Force Generation (Muscle Girths Squared)	Force Application (Shape Characteristics)	Total Weight or "Dead" Weight	(For Force Application)
Candidate Variables			
sf adjusted gluteal girth sf adj. mid-thigh girth muscle mass$^{2/3}$ etc.	mesomorphy proximorphy angularity etc.	total weight adipose weight bone weight etc.	stature thigh length shank length etc.

Table 3.8: Sample of Candidate Variables for Anthropometric Analogue.

Chapters I and II included discussions of how forces exerted by muscles are roughly proportional to the cross-sectional area of the muscle masses. The square of skinfold-adjusted muscle girths may therefore provide a reasonable anthropometric analogue for force production, as might muscle mass raised to the two-thirds power (to retain the dimension $[L^2]$). Chapter II also discussed how shape, particularly across animal species, seems to be related to the effective performances of those animals, perhaps by altering the way in which force production is applied and utilized.

The weight to be accelerated is obviously best measured by total body weight. However, in some samples this may be highly colinear with muscle girths (as it was in this sample), and some index of "dead" (i.e. non-force producing) weight may explain more of the remaining variance while potentially avoiding multicolinearity problems.

Finally, the distance available for acceleration may be proportional to stature or lower extremity length. While it seems tempting to choose lower extremity length automatically, it must be remembered that several researchers have quantified the large role that the trunk has in generating ground reaction forces. Stature is not only easier and more accurate to measure; it may also be theoretically more sound in this case.

A potential limitation of this study is the possibility that the best jump, of the three repetitions of each jump type, may not have represented the best jump of that type of which the subject was capable. In performance-based studies, there is always the potential threat that true maximal performances may not be achieved. However, the results in chapter IV analyzed the likelihood that maximal jumps were achieved.

Finally, a limitation in all research involves the quality of the measurements made. In this case, an in-depth study of the measurement error preceded the modelling process, to ensure that the data were actually worthy of undergoing modelling procedures. An analysis of the errors in this research is contained at the beginning of Chapter IV.

Section 11 - CHARACTERISTICS OF THE IMPULSE PROFILES

The following force-time variables were calculated on the spreadsheets (the numbers and areas refer to the points and areas, respectively, located on figure 2.3, page 87):

1. minimum unweighting force (#3);
2. minimum unweighting force (#3, as a percentage of body weight);
3. peak force (#6);
4. peak force (#6, as a percentage of body weight).
5. impulse deficit (|Area B| minus area A) = impulse debt (Area C);
6. impulse surplus (Area D);
7. final unweighting phase negative impulse (Area E);
8. flight phase 'air time' (#8 to #9).

Descriptive relationships between these variables and the jump heights were sought. Then relationships between the impulse profiles and the anthropometry were similarly investigated. Again, an emphasis was placed on explanatory rather than purely predictive relationships.

Chapter IV

RESULTS AND DISCUSSION

Section 1 - MEASUREMENT ERROR

Pilot Studies:

The major focus of the pilot studies was to assess the feasibility, face validity, and reliability of the non-standard anthropometric measures: i.e. the lower extremity sequential girths (leading to separate thigh and shank angularity indices). A preliminary study was done on a few athletes and sedentary individuals in Barcelona, Spain. Subsequently, a more formal pilot study involved thirty Simon Fraser University students and staff, comprising 16 males and 14 females.

Sequential Girths and Angularity Indices:

The length-adjusted sequential girths, which provided unitless proportional girths for both the thigh and the shank (lower leg), were then used to create the thigh and shank angularity indices (see Table 4.1 below). Figure 4.1 (also below) compares the proportional thigh girths of a very muscular, competitive male body builder, and a sedentary female of approximately the same age. Figure 4.2 does the same for the shank.

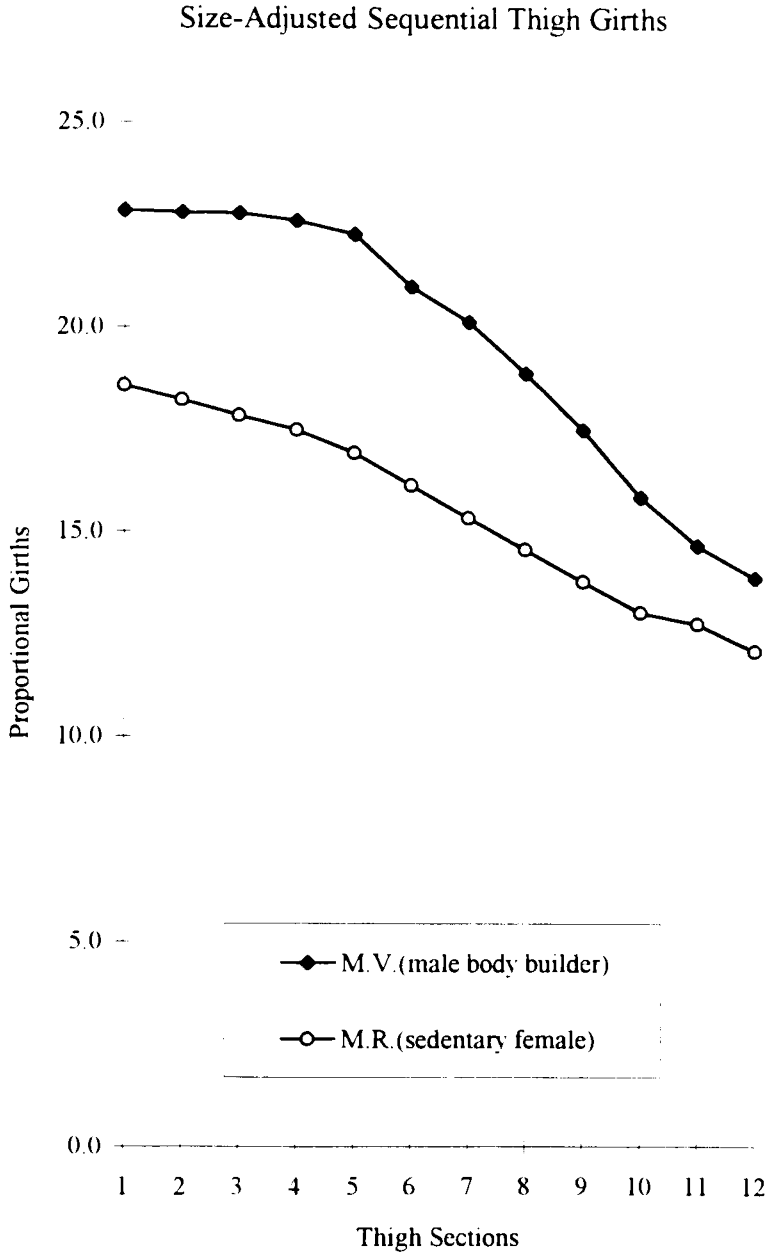

Fig. 4.1: Size-Adjusted, Unitless Sequential Thigh Girths: (see p.139). Sample of a male body-builder and a sedentary female of similar age.

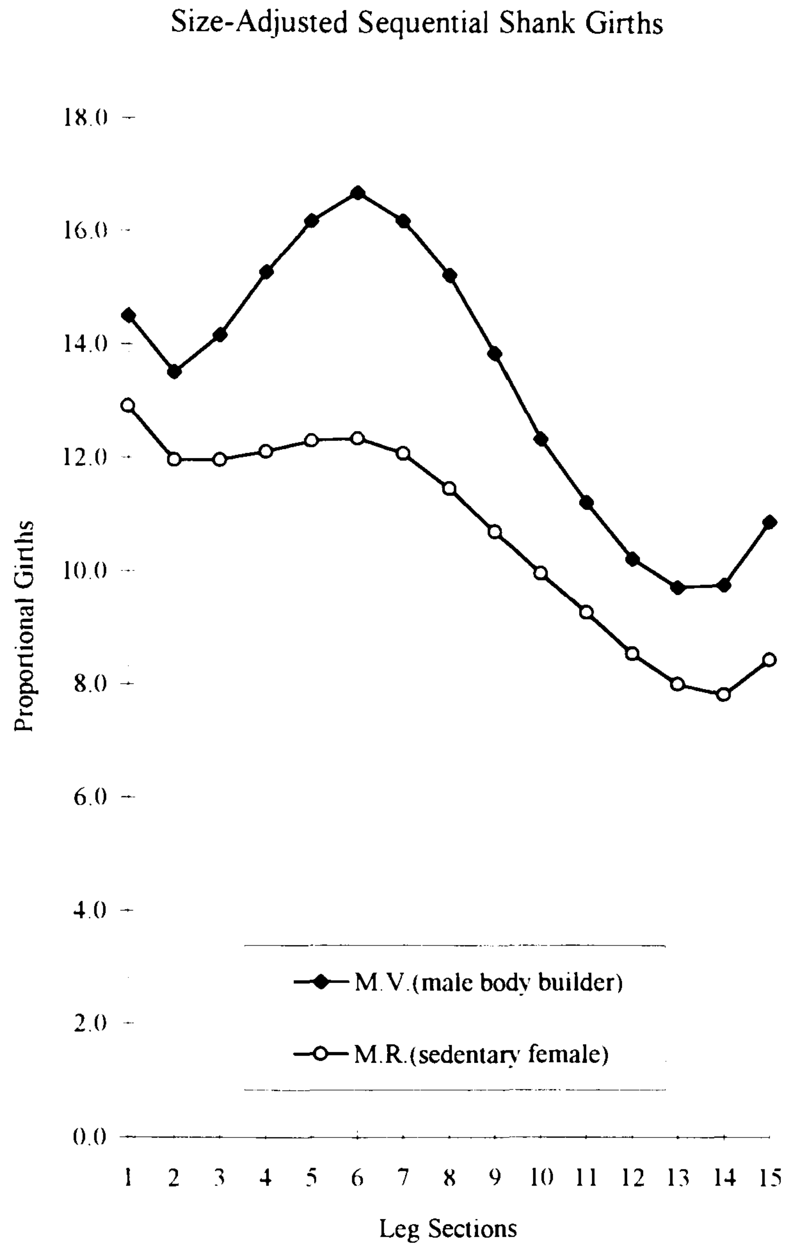

Fig. 4.2: Size-Adjusted, Unitless Sequential Shank (Leg) Girths: (see p. 139). Sample of a male body-builder and a sedentary female of similar age.

Angularity Indices	Thigh	Shank
Male Body Builder	0.99	0.96
Sedentary Female	0.62	0.55

Table 4.1: Sample of Dimensionless Thigh and Shank Angularity Indices.

The sequential girths were measured three times on each subject in the pilot study, and the resultant angularity indices were found to be quite reliable (R = 0.89, according to the reliability coefficient described on page 168 below). Because of the large amount of time required to make these measurements, it was decided that only one series of sequential girths would be taken on each subject in the major study.

Proximorphy Index:

The proximorphy index was based on measurements which are already part of the standard I.S.A.K. protocol. Its reliability was therefore as good as the measurements upon which it was based. The reliabilities of these and the other standard anthropometric variables are listed in table 4.2 below (p. 170).

Reliability of Anthropometry:

As described in Chapter III, 3 measurements were taken for all the anthropometric variables (with the exception of weight, stature, sitting height, arm span, and the sequential lower extremity girth measurements, each of which was measured only once). While the median of the three measures was chosen for modelling purposes, an analysis of the within-subject and inter-subject variation was required to establish the reliability of the data.

Mueller and Martorell (1988) discuss how within-subject variability (called unreliability by Habicht et al. (1979)) has two variance components in anthropometry:

1. imprecision (i.e. measurement error variance)

   This is the within-subject variance, or 'intraobserver variance' (Munro et al., 1966), which occurs when replicate measures are taken within a very short time span, and which is therefore unlikely to be due to physiological variation. This variance is then best explained as measurement error. (It must be acknowledged that replicate skinfold measurements may produce compression effects over a short period of time, but variation is likely to be minimal, and is not true physiological variance anyway, as it results directly from the measurement process.)

2. undependability (i.e. physiological variation)

This is the within-subject variance due to physiological change. This usually occurs over a longer time span, although it may occur daily (as with weight), or within a day (as with height).

The three repeated measures included in this study were taken over a short period of time (i.e. ten minutes or less for any given variable), and so the within-subject variance here was likely to be due to measurement error around an unchanging "true" value; i.e. imprecision.

The technical error of measurement (TEM) has been proposed by Dahlberg (1940), Johnston et al. (1972), Mueller and Martorell (1988) and Knapp (1992) as a useful tool for measuring within-subject variance. It is, in fact, the square root of the within-subject variance, and when replicate measures are taken over a short period of time - thereby minimizing physiological variance - the TEM is then the standard deviation of the measurement error. It is given by the following equation:

$$TEM = (\Sigma d^2/2N)^{0.5} \qquad \text{(Eq. 46)}$$

where:

TEM = the technical error of measurement;
Σd^2 = the difference between each paired comparison of the replicate measures, squared and then summed over the number of comparisons;
N = the number of comparisons.

It should be noted that if 10 subjects were measured twice on a variable, the number of comparisons possible is one per subject (measurement 1 vs measurement 2), and the number of subjects would equal the number of comparisons (i.e. 10). Dividing by $2N$ essentially ascribes the total error (Σd^2) equally to each measurement in the paired comparisons. If 10 subjects were measured three times on a variable, there would now be three comparisons possible per subject (1 vs 2, 2 vs 3, 1 vs 3), or thirty comparisons in all. The total error from these thirty comparisons then would be divided by $2N = 60$, in order to ascribe the error (Σd^2) equally to each measurement.

In this study, triplicate measures were taken on most of the anthropometry, and the median value was chosen for the modelling. However, if the first two measurements on any variable were the same, a third measurement was not taken, since by definition the median had already been determined. The number of measurements per variable thus differed among subjects, and the total number of comparisons also varied. It was decided to eliminate, from the calculation of the *TEM*, the subjects for whom a third measurement was not required, so as not to provide a slight bias by underestimating the variability. These *TEM* results are listed in Table 4.2, below (p. 170).

Johnston et al. (1972) further suggest that since larger measurements are likely to involve bigger errors, it may be useful to express the technical error of measurement relative to the mean value of the variable upon which it is derived. The percent technical error (%TEM) is thus:

$$\%TEM = (TEM/Variable\ Mean)\ X\ 100$$

(Eq. 47)

These are also listed for each anthropometric variable in Table 4.2, p. 170.

Finally, Mueller and Martorell (1988) define a reliability coefficient (*R*) as one that has values ranging from 0 to 1, and that can be estimated by:

$$R = 1 - (r^2/s^2)$$

(Eq. 48)

where:

R = is the reliability coefficient;
r^2 = is the square of the technical error of measurement;
s^2 = is the intersubject variance.

This assesses the amount of measurement error in relation to the variability among subjects, and is an important consideration when attempting to infer statistical significance from the intersubject variability. The reliability coefficients for the anthropometric variables are also listed in Table 4.2. Since the replicate measures were taken over a very short time span, these may also be thought of as *precision coefficients* (Mueller and Martorell, 1988 and Himes, 1989). It is assumed that the errors of measurement of the replicates have a mean of zero, and that they are uncorrelated with the 'true' values and with each other. (To the degree that errors on repeated measurements are correlated, the calculated R will have a tendency to overestimate reliability (Himes, 1989).)

MEASUREMENTS	SUM d^2	N	Mean (cm)	TEM	%TEM	S^2	R
SKINFOLDS (in mm)	**4944.45**	**3458**	**11.05 mm**	**0.846**	**7.652**		
Triceps	403.75	426	9.78 mm	0.688	7.036	21.640	0.978
Subscapular	369.00	441	10.43 mm	0.647	6.204	18.632	0.978
Biceps	134.00	379	4.56 mm	0.420	9.222	4.388	0.960
Iliac Crest	1359.70	473	14.87 mm	1.199	8.062	55.510	0.974
Supraspinale	667.50	445	8.10 mm	0.866	10.686	17.231	0.956
Abdominal	956.00	452	15.38 mm	1.028	6.684	58.960	0.982
Front Thigh	773.50	435	15.72 mm	0.943	5.997	58.894	0.985
Medial Calf	281.00	407	9.55 mm	0.588	6.154	18.076	0.981
DIRECT LENGTHS	**421.12**	**3450**	**39.21**	**0.247**	**0.630**		
Upper Arm	50.26	436	33.67	0.240	0.713	7.815	0.993
Forearm	30.28	430	26.86	0.188	0.699	6.391	0.994
Hand	19.76	408	19.87	0.156	0.783	2.501	0.990
Iliospinale-Box	92.60	460	53.64	0.317	0.591	69.976	0.999
Trochanterion-Box	114.28	458	47.26	0.353	0.747	61.656	0.998
Thigh Length	64.20	424	45.23	0.275	0.608	13.453	0.994
Tibiale Laterale Ht	19.38	426	47.54	0.151	0.317	14.456	0.998
Leg Length	30.36	408	39.60	0.193	0.487	11.158	0.997
Foot Length	18.44	412	26.57	0.150	0.563	4.887	0.995
BREADTHS	**481.47**	**4059**	**19.53**	**0.244**	**1.247**		
A-P Chest Depth	42.96	441	20.44	0.221	1.080	6.773	0.993
Transverse Chest	98.72	436	29.02	0.336	1.159	9.227	0.988
Biacromial Breadth	171.56	460	39.95	0.432	1.081	11.837	0.984
Biiliocristal Breadth	70.34	432	28.14	0.285	1.014	5.016	0.984
Humerus Width	10.97	484	7.21	0.106	1.476	0.424	0.973
Wrist Width	5.86	452	5.97	0.081	1.350	0.230	0.972
Hand Width	15.15	456	8.47	0.129	1.522	0.521	0.968
Femur Width	47.47	486	10.01	0.221	2.208	0.617	0.921
GIRTHS	**1762.63**	**6042**	**47.93**	**0.382**	**0.797**		
Head Girth	27.72	404	56.74	0.185	0.326	3.392	0.990
Neck Girth	141.38	458	37.57	0.393	1.046	15.253	0.990
Arm Relaxed Girth	89.18	459	31.80	0.312	0.980	17.266	0.994
Arm Flexed Girth	27.32	433	33.46	0.178	0.531	21.213	0.999
Forearm Girth	12.26	385	28.29	0.126	0.446	9.242	0.998
Wrist Girth	15.38	423	17.07	0.135	0.790	2.277	0.992
Chest Girth	598.94	483	96.82	0.787	0.813	106.117	0.994
Waist Girth	300.88	479	79.58	0.560	0.704	78.462	0.996
Gluteal Girth	270.36	469	98.09	0.537	0.547	60.850	0.995
Thigh Girth	134.36	459	59.55	0.383	0.642	31.176	0.995
Mid-Thigh Girth	116.64	463	55.19	0.355	0.643	28.848	0.996
Calf Girth	5.62	365	37.38	0.088	0.235	10.088	0.999
Ankle Girth	7.21	339	22.44	0.103	0.460	2.946	0.996

Table 4.2: Precision of Anthropometry on 165 Subjects: Sum of Squared Differences (SUM d^2), Number of Comparisons (N), Variable Mean (cm [SF in mm]), Technical Error of Measurement (TEM), Percent Technical Error (%TEM), Variable Variance (S^2), and Reliability Coefficient (R).

It can be seen from this table that all the anthropometric variables were found to be very reliable, with the lowest *R* coefficient of .921 occurring with femur width. This was partly due to a somewhat higher measurement error (the large muscle mass from the thigh tends to obscure bi-condylar palpation), but also to the relatively small intersubject variance.

The largest errors in relation to the mean value of the variable came from the skinfold measurements, where the *%TEM* ranged between 5 and 11%. However, because the intersubject variance was relatively large with the skinfolds, the resulting reliability ratios were all above 0.96. Ironically, the lowest skinfold reliability was found with the biceps, which actually had the smallest measurement error (*TEM*). This anomaly was due to the very small intersubject variance in biceps skinfolds. (It should be noted here that Table 4.2, p. 170, reflects the *TEM* scores in the units that were used for recording purposes, and which are also normally used for discussion purposes. Thus all *TEM* scores are reported in centimetres except for the skinfolds, which are in millimetres.)

The direct lengths had very low *TEM* scores (<0.4 cm) and *%TEM* scores which were always less than 1%. In every case the *R* coefficients were 0.990 and above. The breadths had similarly low *TEM* scores, but because their mean values were smaller, the *%TEM* scores were slightly higher (between 1.0% and 2.3%). The reduced intersubject variance of the breadths lowered the *R* coefficients somewhat.

The girths had low mean *TEM* scores, with *%TEM* that in only one case (neck girth) exceeded 1%, and with *R* coefficients equal to or greater than 0.990.

The variables with the greatest percent of measurement error were the skinfold measurements, with *%TEM* of between 6% and 11%. However, because of the relatively large intersubject variability of the skinfolds, their reliability coefficients were still all above 0.950.

Figure 4.3 below shows the relationships between the *TEM* and the *%TEM* over all variable types. For ease of comparison on the graph, the *TEM* score for the skinfolds was transformed from millimetres to centimetres, to be consistent with the other variables.

While only one series of sequential girth measurements was taken on each subject in the major study, the triplicate measures in the pilot study showed the angularity indices to be quite reliable (*R* = 0.890; see Table 4.3 below, p. 173).

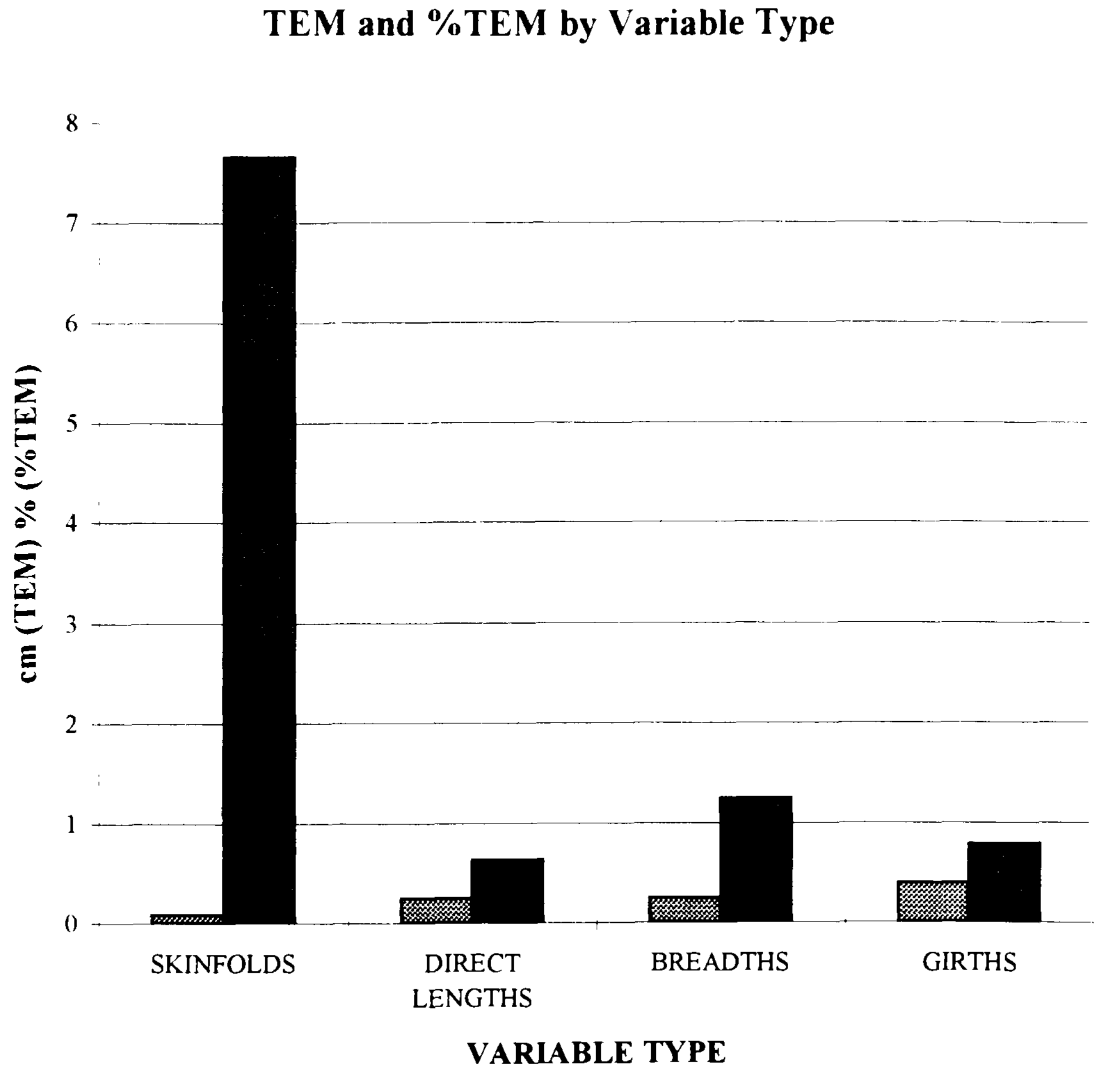

Fig. 4.3: Technical Error of Measurement (TEM) in cm and Percent Technical Error (%TEM) by Anthropometric Variable Type.

	SUM d^2	N	Mean	TEM	%TEM	S^2	R
Angularity Index	.0987	90	0.68	0.023	3.433	0.005	0.890

Table 4.3: Precision of Angularity Indices on 30 Subjects: Sum of Squared Differences (SUM d^2), Number of Comparisons (N), Variable Mean (Mean), Technical Error of Measurement (TEM), Percent Technical Error (%TEM), and Reliability Coefficient (R).

Error in Kerr Fractionation Model:

It is impossible to estimate the error involved in any indirect body composition assessment technique if the procedure has not been validated against an acceptable 'gold standard' (i.e. criterion measures of body composition such as cadaver analyses). Even then, however, validation of a technique on one sample of cadavers does not prove that the technique will work well with a substantially different set of cadavers, or with live humans of different sexes, ages, somatotypes, etc..

Nonetheless, the Kerr technique (Kerr, 1988) shows promise in that it at least acknowledges that a two-component model (e.g. fat mass and lean body mass) is unlikely to be very accurate over a broad range of individuals, mostly because of the likelihood of wide ranges in the *density* of the lean body mass (see Ross et al.,1987; and Adams et al., 1982). A two-component model is also uninformative regarding the *proportion* of the various components in the lean body mass. Based on anthropometry, the Kerr technique fractionates body mass into five anatomical tissue components: skin, adipose, muscle, bone, and residual. And as with any fractionation model, one requirement for its accuracy is that the estimated tissue masses should total to a value very close to each subject's actual mass. (While this does not guarantee the model's accuracy, it is a minimal criterion for its usefulness.) Also, any error that does exist should be unbiased, and unrelated to the amount of any of the individual tissues.

The Kerr fractionation equations were applied to the 165 subjects of this research, to determine the estimates of their five tissue masses. The tissue estimates were summed to estimate total mass for each individual. Each subject's actual mass was then subtracted from the estimated total mass to derive an error mass, and this error mass was then expressed as a percentage of the actual total mass. The procedure appeared to work well with all but the nine pre-pubertal figure skaters, for whom the errors were quite large (i.e. 15% - 33%). They were left out of the analysis of the error scores described below.

Table 4.4 (below) shows the descriptive statistics of the remaining error percentages, with the mean absolute error (2.83%) indicating small error magnitude (i.e. within the 5% TEM range sought for most of the anthropometry upon which the Kerr model is based). The mean constant error, which indicates bias, was extremely small at -0.54%. Scatterplots of the error scores versus each estimated tissue mass and total mass are homoscedastic, showing no bias or unusual trends. (Figure 4.4 (below, p. 176) is one such example - the plot of error versus total actual body mass.)

DESCRIPTIVE STATISTICS OF KERR FRACTIONATION ERROR SCORES	
N	156
MEAN ABSOLUTE ERROR (Error Magnitude)	2.83%
MEAN CONSTANT ERROR (Error Bias)	-0.54%
S.D.	2.60%
S.E.M.	0.20%
MINIMUM	-10.38%
MAXIMUM	15.47%
RANGE	25.85%

Table 4.4: Descriptive Statistics of Kerr Fractionation Error Scores

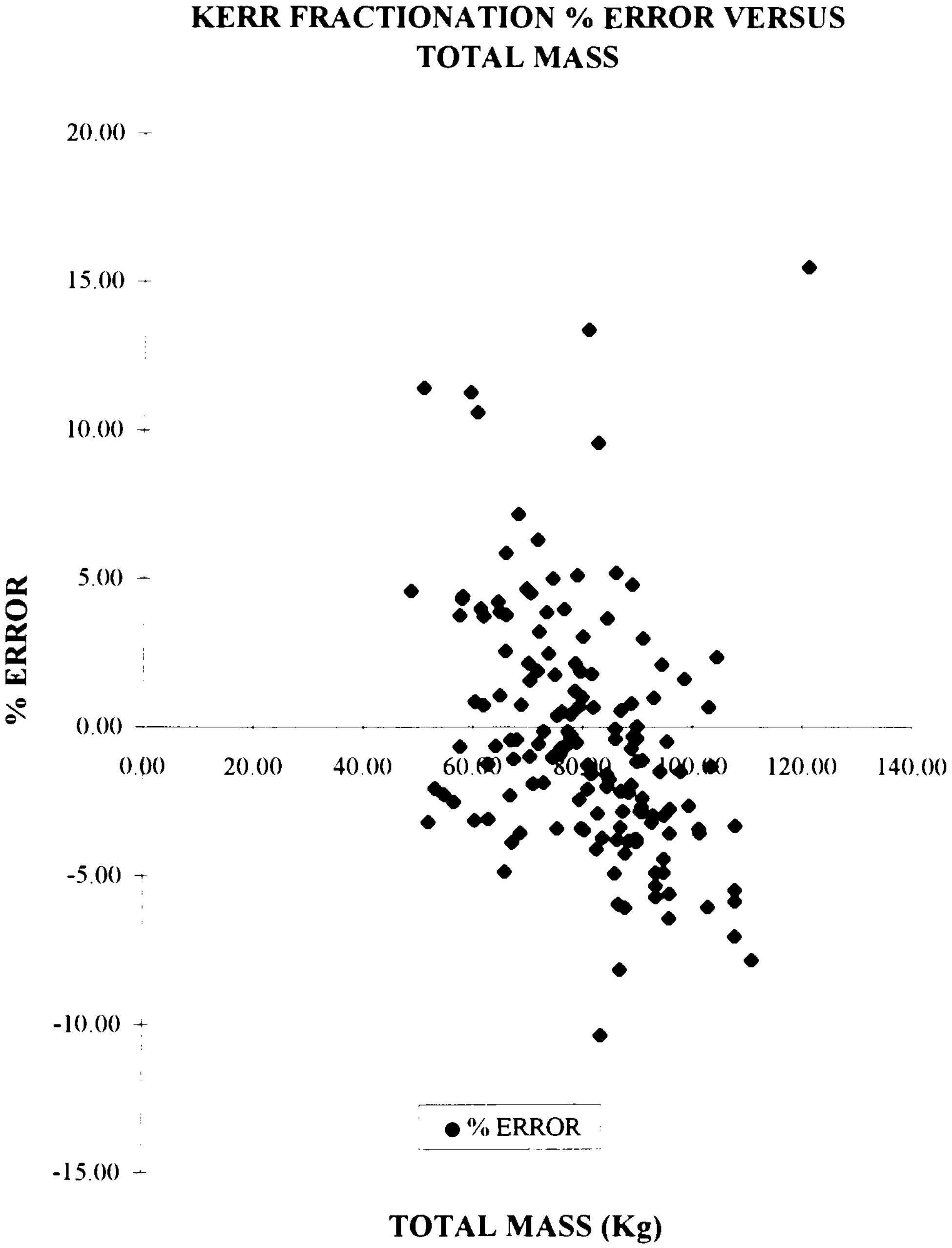

Figure 4.4: Kerr Fractionation % Error Versus Total Mass.

Distributions of Anthropometric Data:

Probabilty plots were produced for all the anthropometric variables. Each variable was plotted along the abscissa, against the corresponding expected values of a theoretical normal distribution on the ordinate. Normally distributed data forms a more or less straight line running from the bottom left corner of the graph to the top right corner. Figure 4.5 (below) shows the probability plot for the corrected mid-thigh girth, and indicates a fairly normal type distribution.

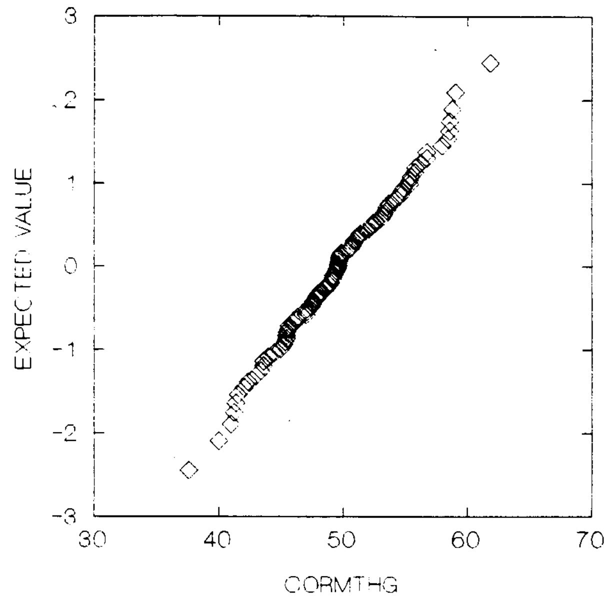

Figure 4.5: Probability Plot for Skinfold-Corrected Mid-Thigh Girth.

All of the anthropometric data were quite normally distributed, with the exception of the skinfolds, which were all very positively skewed. This is common for skinfolds, and is especially likely to be encountered in very lean and fit samples of subjects, such as in this research. Figure 4.6 (below) shows the probability curve for the mass-adjusted sum of skinfolds.

Since many statistical procedures are based on the assumption of normally distributed data, the mass-adjusted sum of skinfolds were transformed to $\log_{(10)}$, and this improved the distribution considerably (see figure 4.7 below).

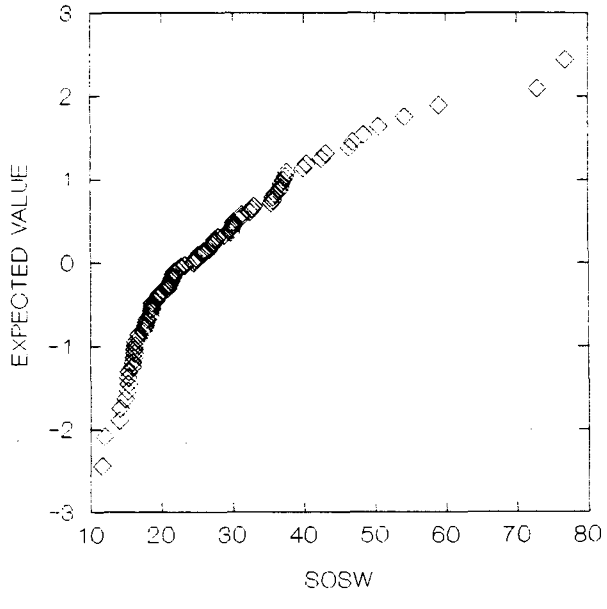

Figure 4.6: Probability Plot for the Mass-Adjusted Sum of Skinfolds.

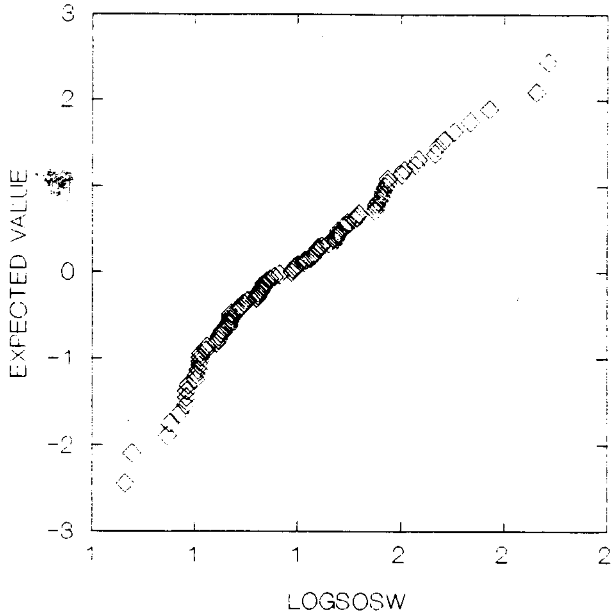

Figure 4.7: Probability Plot for the Transformed $Log_{(10)}$ Mass-Adjusted Sum of Skinfolds.

Evidence for Geometric Versus Elastic Similarity:

Chapter II (p. 34) presented the argument proposed by McMahon (1975) and others, that as the height of animals increases along the 'mouse-to-elephant curve', transverse plane linear dimensions may increase faster than height, in order to provide better support for a more rapidly increasing mass. This is the premise behind the elastic similarity system.

The use of the Ross-Wilson 'phantom' proportionality scores in this study required that a decision be made whether to assume scaling on a geometric or elastic similarity system. If increasing height within the human species produced proportionally greater transverse plane dimensions, as it appears to do across species, the 'phantom' z scores based on geometric similarity would show increases with greater heights. They do not! In fact, they diminish with increasing heights.

In this study, the Pearson correlation coefficient between stature and thigh girth z scores (based on assumptions of *geometric* similarity) was -0.234 ($p < 0.05$), and between stature and calf girth z was -0.268 ($p < 0.01$). The correlation between stature and femoral breadth z scores was also negative (-0.011) but was not significant. Figures 4.8 and 4.9 (below, p. 181) are scatterplots showing these relationships between stature and thigh girth z scores, and stature and calf girth z scores, respectively. Figure 4.10 shows the relationship between stature and calf girth z scores that are based on elastic similarity.

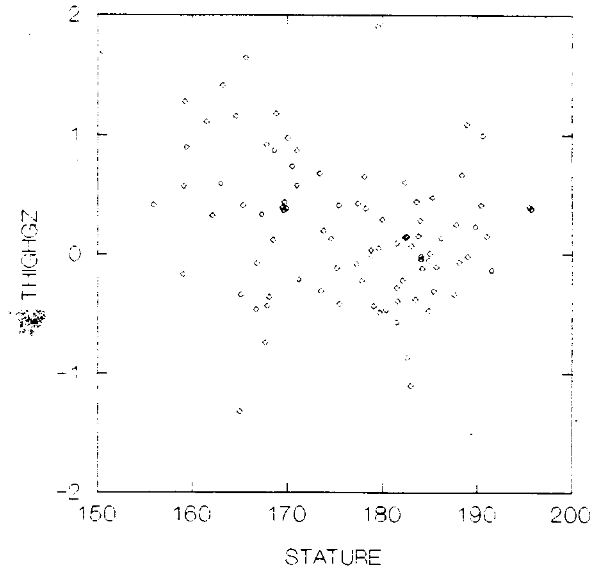

Figure 4.8: Scatterplot of Stature Versus Thigh Girth Z (Based Upon *Geometric* Similarity). Stature is in cm. The Pearson correlation coefficient is -0.234 ($p < 0.05$).

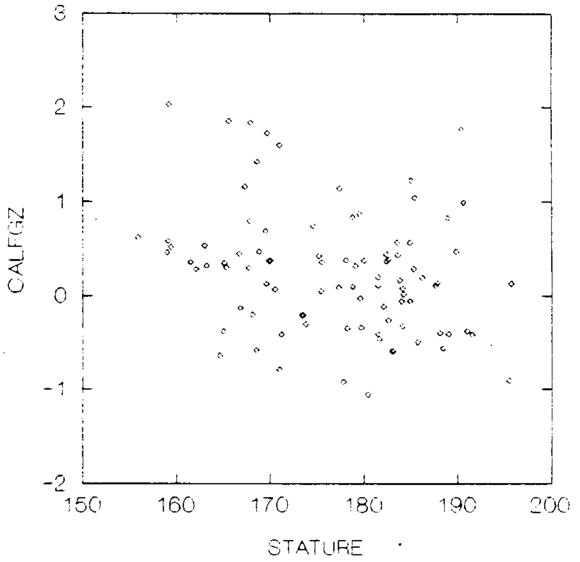

Figure 4.9: Scatterplot of Stature Versus Calf Girth Z (Based Upon *Geometric* Similarity). Stature is in cm. The Pearson correlation coefficient is -0.268 ($p < 0.01$).

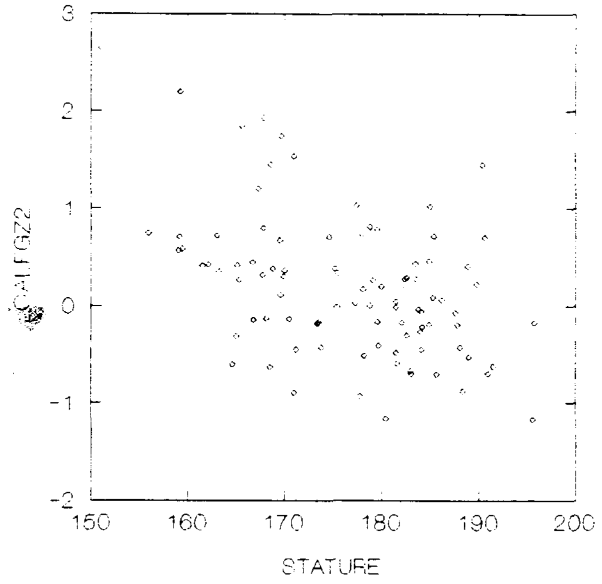

Figure 4.10: Scatterplot of Stature Versus Calf Girth Z (Based Upon *Elastic* Similarity). Stature is in cm. The Pearson correlation coefficient is -0.409 ($p < 0.001$).

These findings are consistent with Ross et al. (1987), and with the last century view of Adolphe Quetelet (1833), that taller humans are more linear than shorter ones. They further suggest that the support structures of taller humans are *not* proportionally more massive, as would be expected by an elastic similarity system, but in fact are less so. In other words, the forces that drive natural selection and species differentiation along the 'mouse-to-elephant curve' do not appear to be reflected in the biological diversity within the human species at a given snapshot moment in time (at least for the proportionality of support structures). As a consequence, a geometric similarity model appeared to be a more appropriate approach for standardizing differences in size in this study.

Reliability of Force Platform Data:

Normally, a force platform should be calibrated by known weights just before being used for data collection purposes. This allows for the determination of an offset value (i.e. the millivolt reading at zero force) and the establishment of a scale for converting from the millivolt units (captured here by the Labtech Notebook data acquisition software from the charge amplifier) to the Newton units of force.

The offset value and scale may change over time, however, since the amplifier output is sensitive to changes in ambient temperature and humidity. The data collection sessions in this research frequently occurred over long periods of time (e.g. with an average of 1.25 hours per subject to complete the anthropometry and the vertical jumps, it took approximately 10 hours to complete eight subjects). Frequent recalibration would thus normally have been necessary, and this itself would have been a time-consuming process.

Instead, the three second force data collection period per jump was used to include a steady, standing reference line just before each jump was taken. With the subject's weight known, this allowed for a jump-by-jump updated calibration of the force output. While occasionally subjects would not be motionless enough before a jump to provide a good horizontal standing weight calibration line, all subjects were able to provide this at least once out of the nine jumps (and usually much more frequently). For the occasions where no good calibration line preceded the jump, calibration was taken from one of that subject's other jumps.

A macro was written to:

1. adjust the offset to zero (i.e. where zero force gives a zero reading);
2. convert the millivolt units to Newtons of force from the horizontal standing weight calibration data.

This macro is shown in Table 4.5 below.

The variation in the Newtons/millivolt ratio across subjects provided one way of assessing error in the force platform data. Because it is a ratio, however, it cannot be said whether the variation is due to error in the numerator or in the denominator. Any inaccuracy in the scale weight, or in the standing weight horizontal reference line in the force platform data due to movement, would have introduced error to the numerator. Any variation in the millivolt output for a given force would have contributed error to the denominator. The variation in this ratio thus represents a composite error which, while difficult to interpret, is still useful in the determination of the overall force platform reliability.

Figure 4.11 (below) shows the variation in the Newtons/millivolt ratio across all jumps. Table 4.6 provides descriptive statistics for this composite error. Since in theory all jumps should show the same Newtons/millivolt ratio (the amplifier settings remained constant) the standard deviation of this ratio can be taken as the *TEM* for the force platform system in measuring weight. The intersubject variance in weight can then be used to determine a reliability estimate for the force platform in determining weight. The *TEM*, *%TEM* and *R* values are listed in Table 4.6. As can be seen, the error here is really very small (%TEM=1.12%, R=0.999), and the jump data appear useful for modelling purposes.

NEWTONS (a)	COMMENTS
=SELECT("C[1]")	Select column to right
=INSERT(1)	Insert column
=SELECT("R[604]C[-1]")	Select MINIMUM
=COPY()	Copy MINIMUM
=SELECT("RC[1]")	Select cell in new column
=PASTE.SPECIAL(3.1.FALSE.FALSE)	Paste special value to new MINIMUM
=CANCEL.COPY()	Cancel copy
=SELECT("R[2]C")	Select new column MEAN
=FORMULA("=RC[-1]-MINIMUM")	Formula: original MEAN - MINIMUM
=SELECT("R[-604]C")	Select new column cell in row 3
=FORMULA("=RC[-1]-MINIMUM")	Formula: original cell - MINIMUM
=SELECT("RC:R[600]C")	Select rest of range in new column
=FILL.DOWN()	Fill down
=COPY()	Copy adjusted force data
=SELECT("RC[-1]:R[600]C[-1]")	Select original column force range
=PASTE.SPECIAL(3.1.FALSE.FALSE)	Paste values for adjusted force
=CANCEL.COPY()	Cancel copy
=SELECT("R[604]C[1]")	Select adjusted MEAN
=COPY()	Copy adjusted MEAN
=SELECT("RC[-1]")	Select MEAN cell in original column
=PASTE.SPECIAL(3.1.FALSE.FALSE)	Paste value for adjusted MEAN
=CANCEL.COPY()	Cancel copy
=SELECT("R[-604]C[1]:R[1]C[1]")	Select range of cells in new column
=CLEAR(1)	Clear these cells
=SELECT("R[605]C[-1]")	Select N mv cell in original column
=COPY()	Copy N mv cell
=SELECT("RC[1]")	Select cell in new column
=PASTE.SPECIAL(3.1.FALSE.FALSE)	Paste value to adjusted N mv cell
=SELECT("R[-605]C")	Select new column cell in row 3
=CANCEL.COPY()	Cancel copy
=FORMULA("=RC[-1]*N mv")	Formula: Adjusted Force X N mv
=SELECT("RC:R[600]C")	Select rest of new column range
=FILL.DOWN()	Fill down
=COPY()	Copy Newtons of force
=SELECT("RC[-1]:R[600]C[-1]")	Select original column force range
=PASTE.SPECIAL(3.1.FALSE.FALSE)	Paste special values for Newtons
=CANCEL.COPY()	Cancel copy
=SELECT("C[1]")	Select new column
=EDIT.DELETE(1)	Delete new column
=SELECT("R[608]C")	Select cell below column to right
=RETURN()	Return

Table 4.5: Microsoft Excel Version 4.0 Macro for Converting Offset Millivolts to Zero-Offset Newtons.

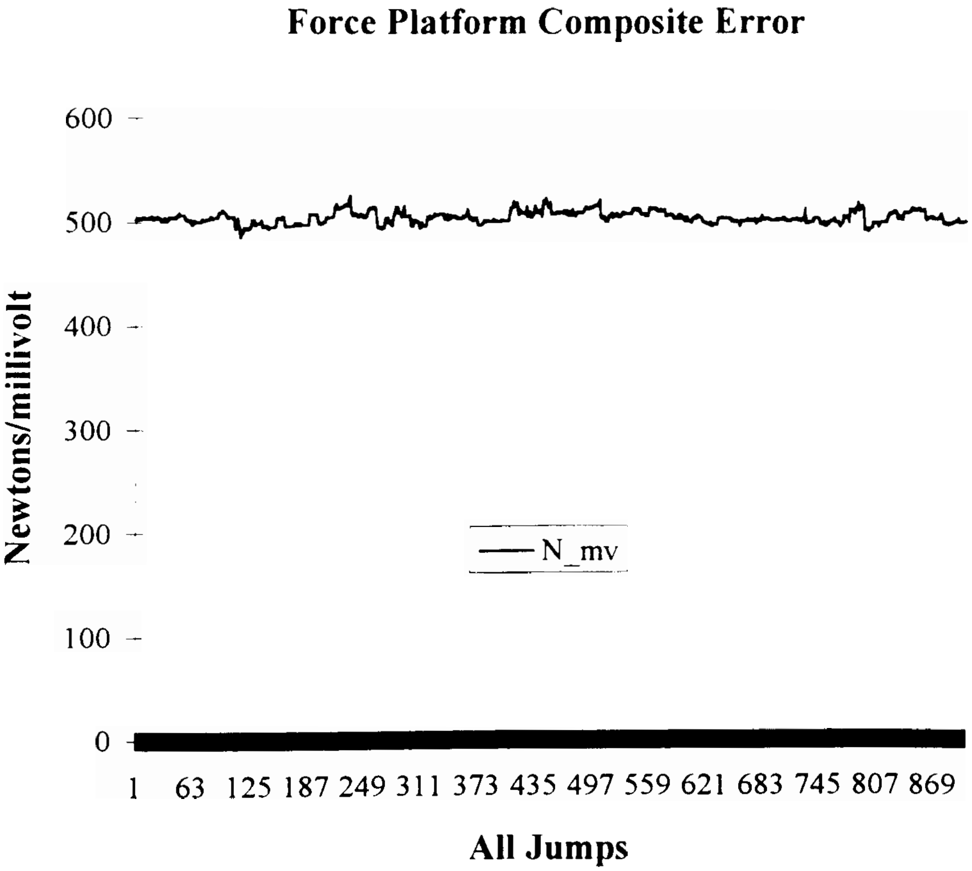

Fig. 4.11: Force Platform Composite Error: Graph shows small error (*TEM* = 1.12%. n = 905).

Force Platform Newtons/Millivolt Ratios	**Descriptive Statistics**
Mean	503.3
Standard Error	0.18
Median	502.9
Mode	494.8
Standard Deviation	5.6
Sample Variance	31.58
Range	39.0
Minimum	484.8
Maximum	523.9
Sum	455525.3
Count	90
Confidence Level (95%)	0.36
TEM	5.6
%TEM	1.12
R	0.99

Table 4.6: Descriptive Statistics of Force Platform Error

Reliability of Force Mat Data:

Due to unforeseen circumstances, it was not possible to do an in-depth study of the force mat error, to assess either its reliability or its validity. However, these data were not used to derive the models, but only to test them, and any *systematic* difference between the force mat and force platform data would merely weaken support for the model's coefficients, rather than for the explanatory variables themselves.

Even so, it was possible to do a rough assessment of the force mat data since five of the hockey players jumped on both the force platform and the force mat (on separate occasions). The maximal jump heights for these five subjects in all three types of jumps on the force platform were compared against the same subjects' maximal jump heights obtained at different times on the force mat. The number of comparisons was thus 15 (5 subjects times 3 jump types). While summary statistics are found in Table 4.7 below, it should be remembered that an *n* of 15 is much too small to make conclusive judgements. The force mat appeared to produce slightly higher jump heights, but they were different jumps, so it's possible that they *were* actually higher.

Maximal Jump Heights Obtained at Different Times on 5 Subjects by 3 Jump Types	Force Platform	Force Mat
N	15	15
MEAN (metres)	0.34	0.38
S.D. (metres)	.04	.05

Table 4.7: Force Platform and Force Mat Comparisons.

Section 2 - THE MAJOR STUDY

Analysis of the Jump Series:

Chapter II included discussion of an assumption that a series of repeated vertical jumps would be subject to two opposing trends: performance increases due to warm-up effects and learning, and performance decreases due to fatigue and boredom. If each trend is represented by a theoretical curve, a maximal jump should occur at the intersection of the two curves. It was assumed that nine vertical jumps (each separated by one minute rest) would include the point of intersection of these curves. In other words, that nine jumps (three of each type) would ellicit a good estimate of the maximal jump of each type for which a subject was capable. An analysis of the results of the series of nine jumps was required to investigate the validity of this assumption.

Figure 4.12 (below) shows the means of the nine jumps across all subjects. The standard error bars all overlap, and a one-way anova showed no significant difference among the jumps ($p = 0.96$). However, since the order of types of jumps was randomized according to the quasi-magic square design discussed in chapter III, each jump number consisted of varying numbers of all three types of jumps. Any height difference from jump types would increase the within-jump-number variance and reduce the likelihood of obtaining a significant difference among the jump numbers even if a real difference existed. In other words, a type II statistical error was possible with this analysis.

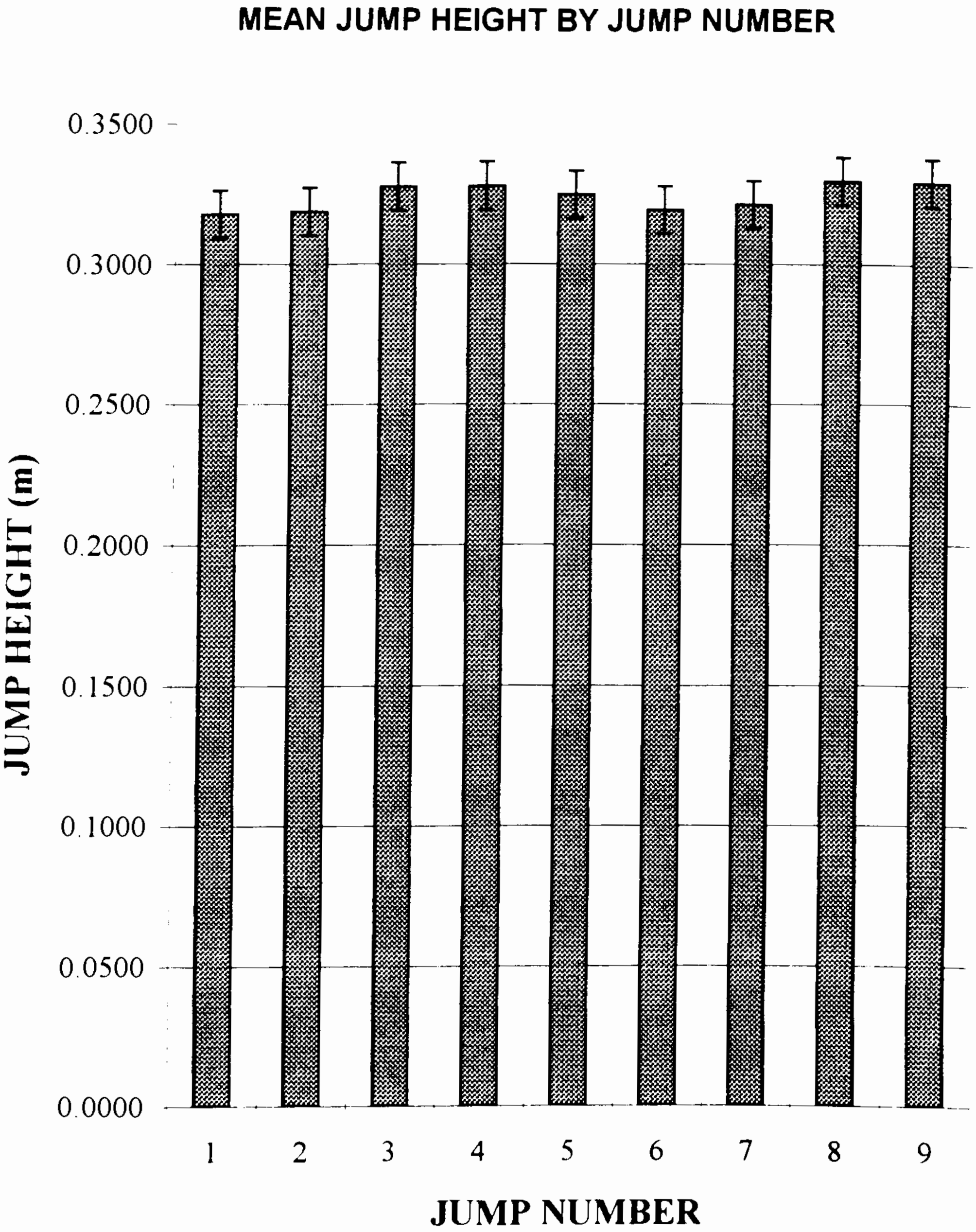

Fig. 4.12: Mean Jump Height By Jump Number: Means of the nine jumps across all 100 subjects, with standard error bars showing no significant difference among the jumps.

A second approach to the analysis separated the jumps into their different types. Also, the figure skaters were eliminated for two reasons: (1) their young ages (mean = 12.03 years) resulted in their jump heights being appreciably less, and (2) possibly also because they were young, they seemed to have great difficulty performing the static jump, and many of them could not meet the criterion (minimum unweighting force > 80% of body weight until maximal velocity at point 7 on the impulse profile) for the successful completion of even one. Individual static jumps by other subjects were also eliminated if they did not meet this criterion. It could reasonably be argued that the static jumps herein represented one end of a continuum of counter movement jumps (i.e. the end which has minimal counter movements).

Figure 4.13 (below) shows the mean heights and standard errors of the three static jumps across all subjects except the figure skaters, with all unsuccessful jumps eliminated. There was no significant difference among the means of the three static jumps ($p = 0.71$).

Figures 4.14 and 4.15 (below) show the mean heights of the counter movement and reach jumps respectively, with their associated standard error bars. There were no significant differences among jump numbers for each type ($p = 0.68$ for the counter movement, and $p = 0.72$ for the reach). However, trends toward increasing height over time for both the counter movement and reach jumps can be seen, and the assumption that the maximal heights for these jumps were obtained cannot be completely supported. The static jump, which is a more unusual skill to perform and which may therefore have a longer learning curve associated with it, or a longer performance improvement curve (see Magill, 1989, p. 50), may produce higher jumps over a greater number of trials.

On the other hand, the slight increase seen in the third jump of each type, if due to more than random error, may result from a 'finishing kick' behaviour. The researcher did remind each subject when the third series of jumps began, and attempted to provide additional motivation to attain maximal jump heights. Specifically, the subjects were told:

> "These are your last three jumps coming up. There's one of each type left. Go as high as you can!"

It must be remembered that the upwards trend is not statistically significant, and even if it were more than a *by chance* phenomenon, it may simply be a result of a number of subjects giving all they had for the last jumps.

Whatever the cause of the trend, the question of whether or not true maximal jumps were attained remains as a minor limitation of the study.

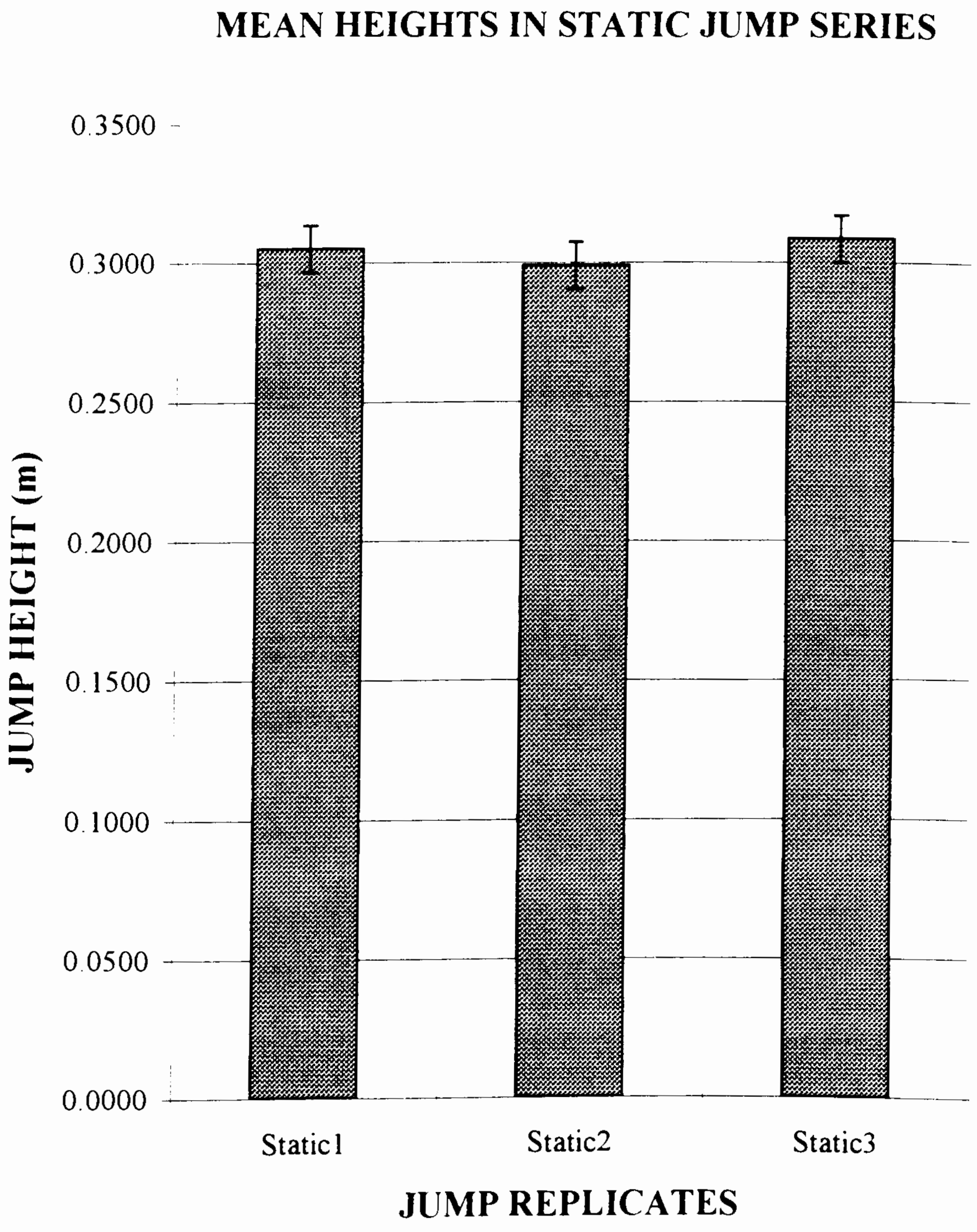

Fig. 4.13: Mean Heights in Static Jump Series: Associated standard error bars show no significant difference among jump numbers ($p = 0.71$).

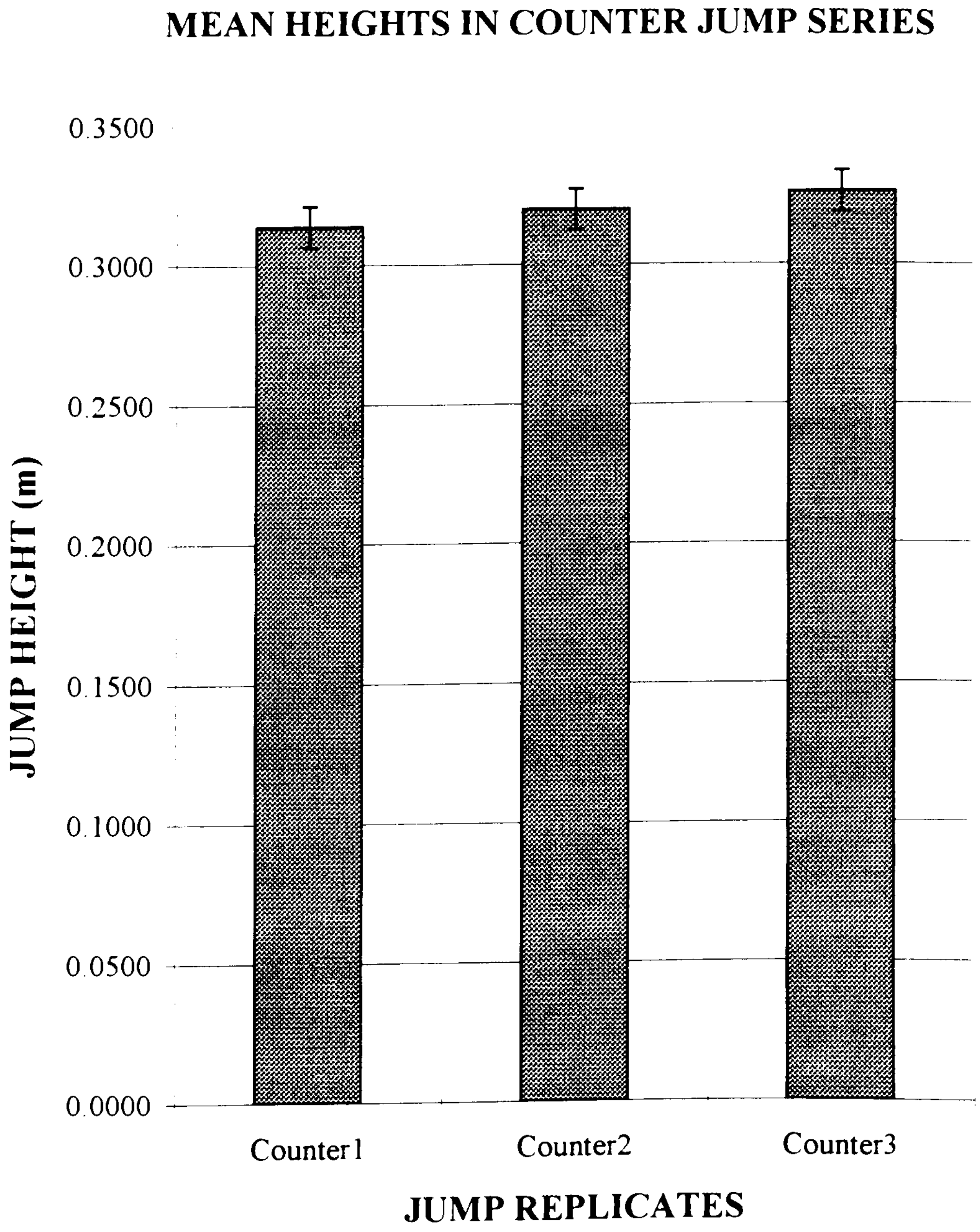

Fig. 4.14: Mean Heights in Counter Movement Jump Series: Associated standard error bars show no significant difference among jump numbers (p = 0.68).

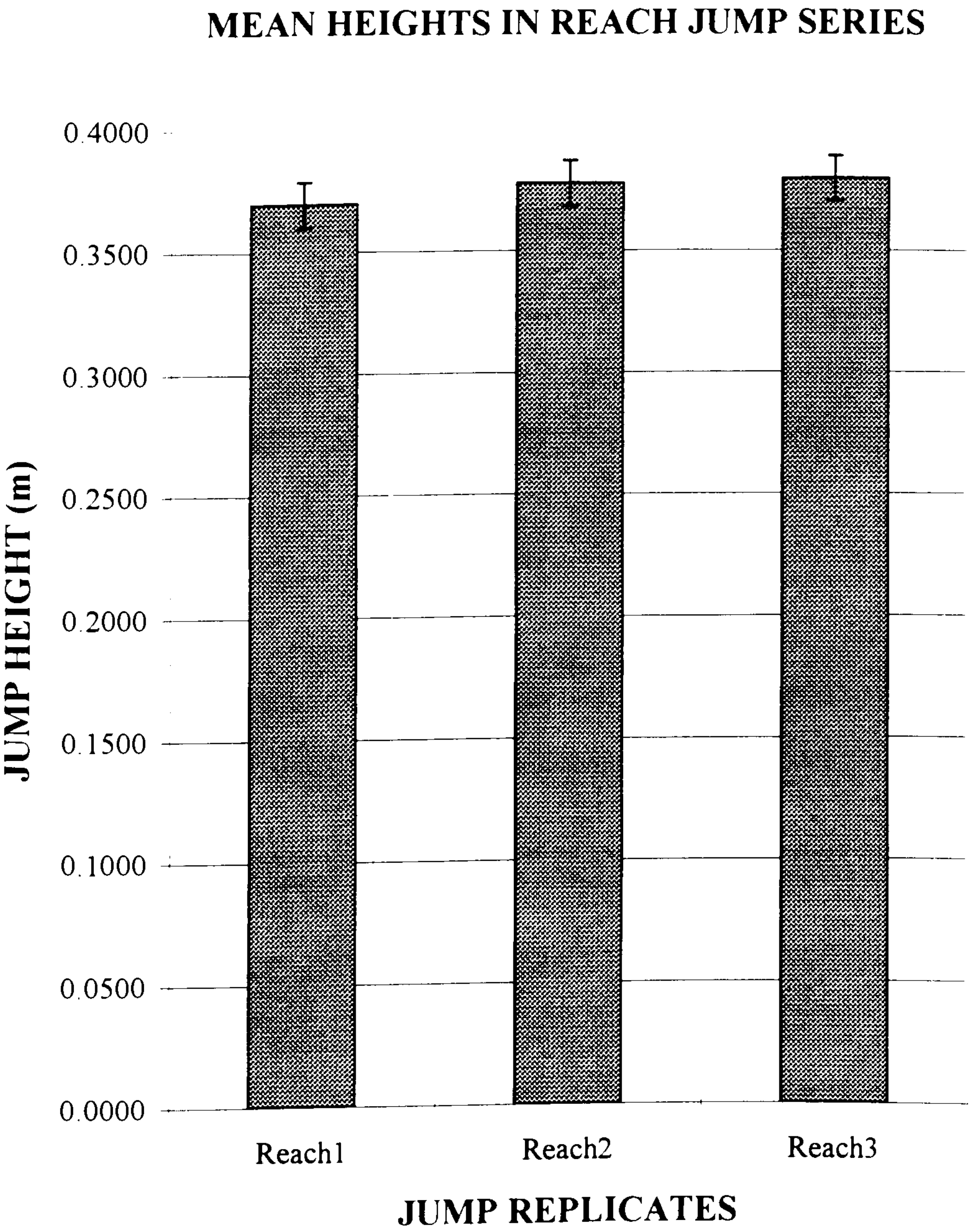

Fig. 4.15: Mean Heights in Reach Jump Series: Associated standard error bars show no significant difference among jump numbers ($p = 0.72$).

Analysis of the Maximal Jumps of Each Type:

The maximal height achieved in each jump type was taken as the best estimate of the individual's present capacity for performing that type of jump, and was then used as the dependent or predicted variable for the modelling.

Table 4.8 (below) summarizes the descriptive statistics of the maximal heights attained in the three jump types. The means and standard error bars are shown in figure 4.16 below. The nine young figure skaters were excluded for all jumps. Three others were excluded from the static jump by virtue of not being able to perform it according to the minimal criteria: i.e. *GRF* > 80% of *W* until maximal velocity at point 7 on the impulse profile.

	STATIC	**COUNTER**	**REACH**
N	88	91	91
MEAN (m)	.3124	.3399	.3950
S.D. (m)	.0682	.0688	.0889
S.E.M. (m)	.0073	.0072	.0093

Table 4.8: Descriptive Statistics of Maximal Jumps by Jump Type.

The direction of the results was consistent with most of the research discussed in chapter II. The countermovements produced higher jumps than those obtained from a static technique. The "reach" technique employed here also had the benefit of a countermovement, and in addition gained from the transfer of momentum from the upward swing of the arms as they reached the end of their range of motion.

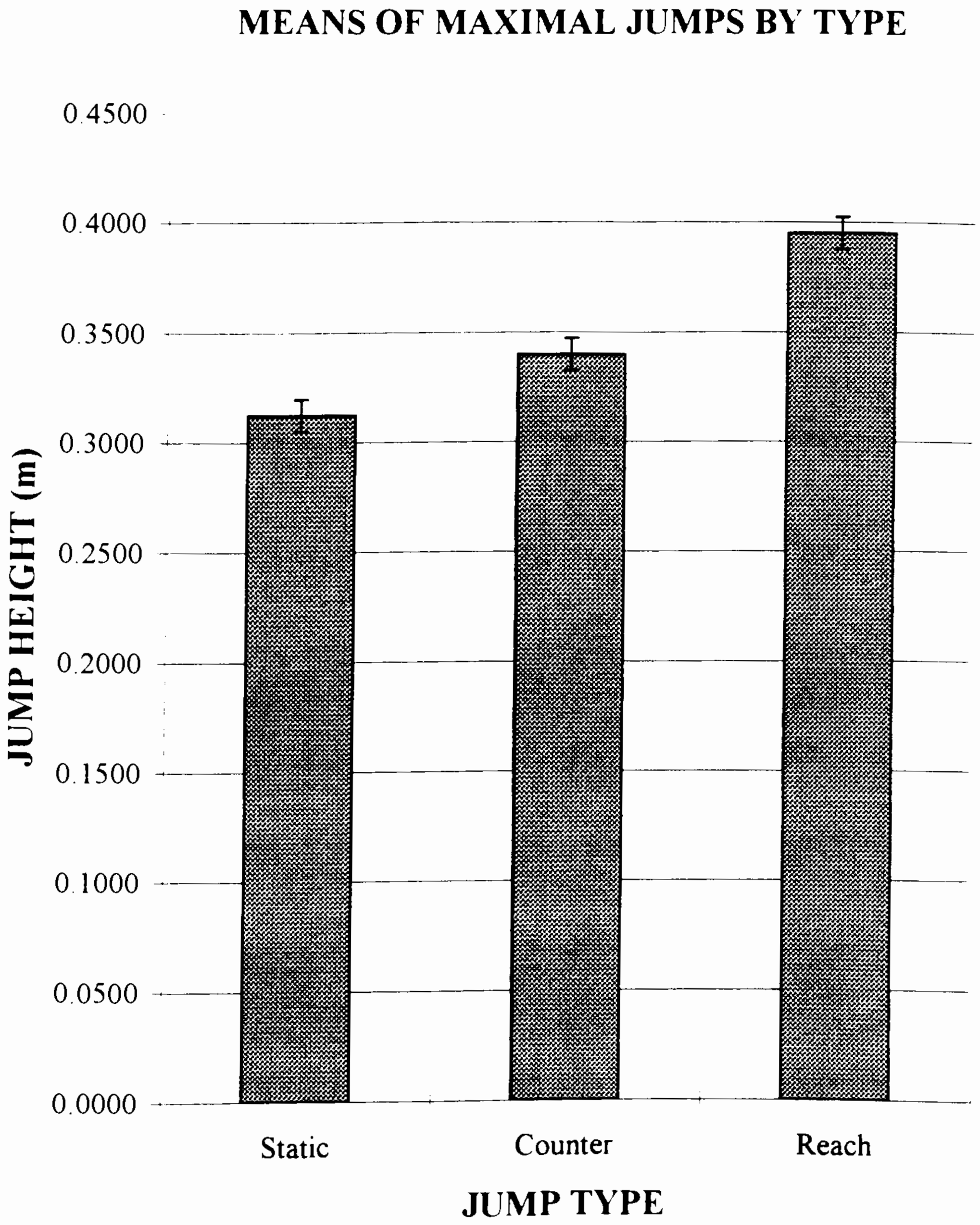

Fig. 4.16: Means of Maximal Jumps By Type (m): Mean heights, and associated standard error bars, of the maximal jumps obtained from each jump type series.

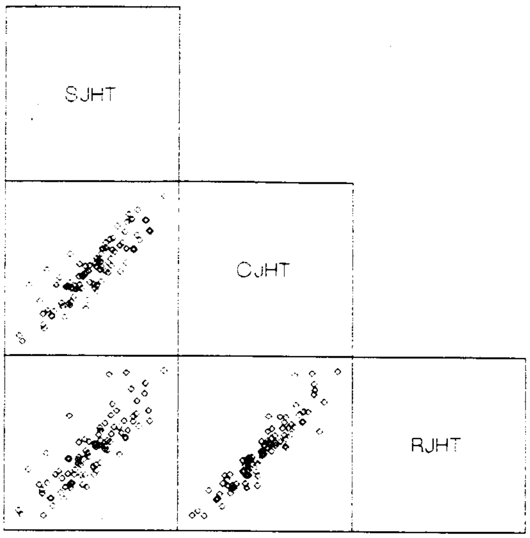

Fig. 4.17: Scatterplot Matrix of Maximal Jumps of Each Type:
SJHT (static jump height);
CJHT (counter jump height);
RJHT (reach jump height).

JUMP TYPE	SJHT	CJHT	RJHT
SJHT	1.000		
CJHT	0.879	1.000	
RJHT	0.840	0.934	1.000

Table 4.9: Correlation Matrix of Maximal Jumps of Each Type.

The scatterplot matrix (Figure 4.17 above) and correlation matrix (Table 4.9 above) of the maximal jumps of each type showed significant high correlations between all pairs of comparisons (with Bonferroni-adjusted probabilities for multiple comparisons all found at $p < .0005$). This suggests that the characteristics which determine the better jumpers in one type of jump will enable them to do well at the other types, too. It also suggests that anthropometric models attempting to predict jump heights in the three techniques may well have the same structural predictors.

As both the plots and the table show, however, the relationship between the counter and reach jumps was even closer than the other two relationships. This may have resulted from both of these jumps having a counter movement, while the static jump did not. An advantage of the overall high intercorrelations was the increased likelihood that a single set of anthropometric variables could predict all three types of jumps.

Prediction of Jump Height from Other Jump Types:

Table 4.10 (below) includes the six possible models of predicting one type of jump from another, using linear equations of the form

$$JUMP\ Y = CONSTANT + (COEFFICIENT \times JUMP\ X) \quad \text{(Eq. 49)}$$

More complete statistics for these regression equations are found in Appendix A.

EQUATION	MULTIPLE R	STANDARD ERROR OF ESTIMATE	S.E.E. AS PERCENT OF MEAN
SJHT = 0.018 + (0.869 CJHT)	0.879	0.033 m	11 %
SJHT = 0.058 + (0.644 RJHT)	0.840	0.037 m	12 %
CJHT = 0.061 + (0.890 SJHT)	0.879	0.033 m	10 %
CJHT = 0.055 + (0.722 RJHT)	0.934	0.025 m	7 %
RJHT = 0.052 + (1.096 SJHT)	0.840	0.049 m	12 %
RJHT = -0.015 + (1.207 CJHT)	0.934	0.032 m	8 %

Table 4.10: Prediction of Each Jump Type from the Others

The ratio of the means of the jumps is shown by table 4.11 below:

JUMP TYPE	RATIO OF MEANS
STATIC JUMP HT.	100%
COUNTER JUMP HT	109%
REACH JUMP HT.	126%

Table 4.11: Ratio of Means of Maximal Jumps of Each Type

Jump Height Distributions:

The jump height distributions were checked for skewness and the presence of outliers. Figures 4.18, 4.19 and 4.20 (below) show the normal probability plots of the maximal static, counter movement and reach jumps. The relatively straight lines extending from the bottom left corner of each graph to the top right corner show that all the maximal jump heights were quite normally distributed in this sample, with no skewing or unrealistic outliers.

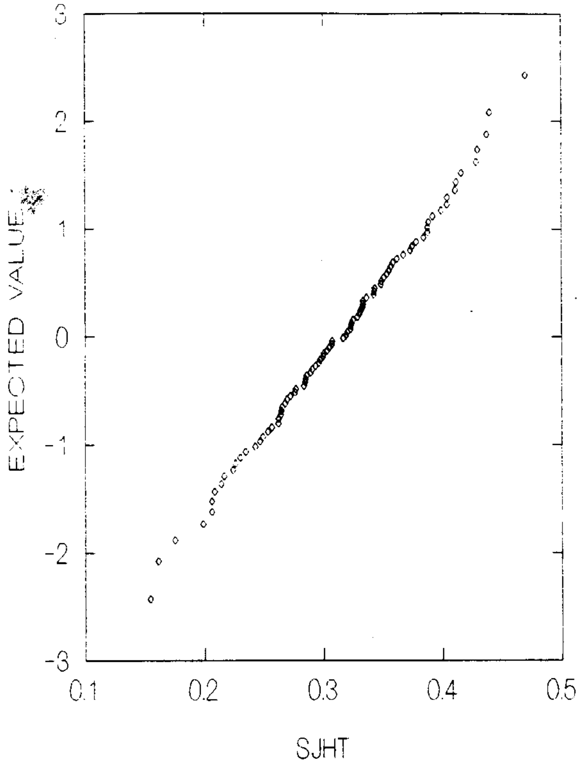

Figure 4.18: Probability Plot for Maximal Static Jump Heights (m).

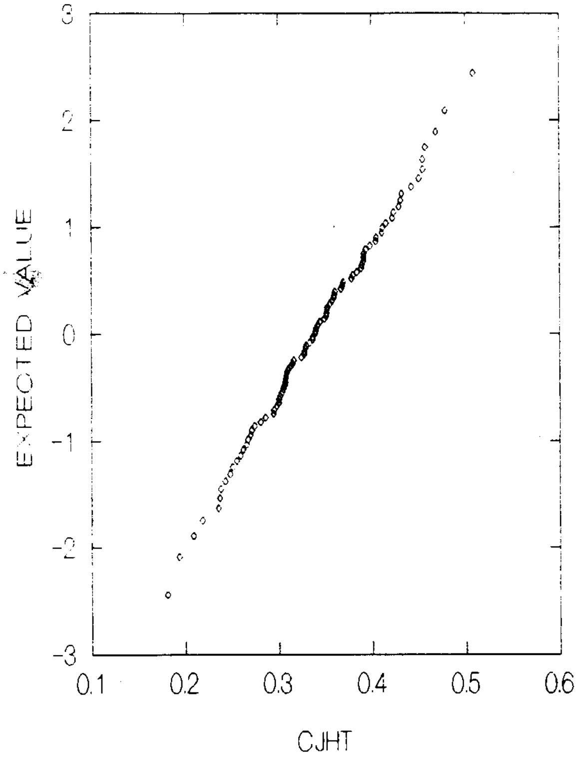

Figure 4.19: Probability Plot for Maximal Counter Movement Jump Heights (m).

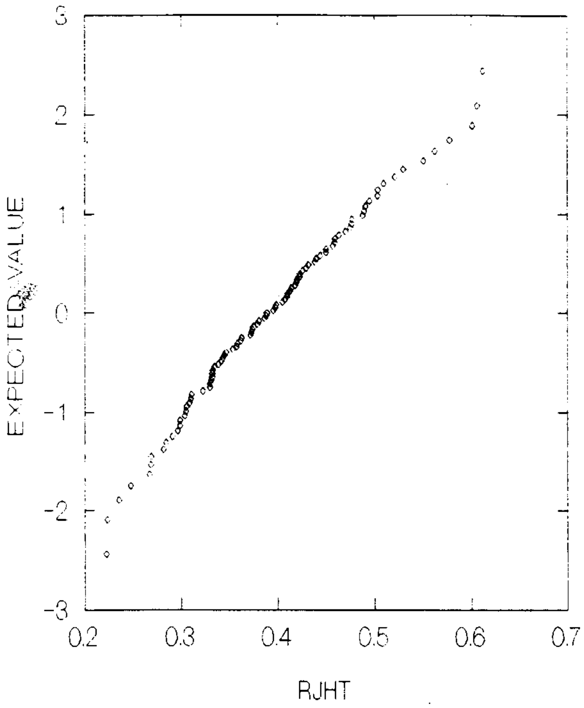

Figure 4.20: Probability Plot for Maximal Reach Jump Heights (m).

Prediction of Jump Height from Time in the Air:

In Chapter II, page 56, an equation was derived for predicting jump height from time in the air, based upon the assumption that the centre of mass lands at the same height from which it took off. This equation is repeated below:

$$d_v = \frac{gT^2}{8} \qquad \text{(Eq. 23)}$$

where:

g = acceleration due to gravity;
T = total time in the air;
d_v = displacement up = absolute value of displacement down.

A comparison was made of the predicted jump heights from this equation with the criterion jump heights (calculated from the net upward impulse). The comparison was made over all three trials for all three jump types for the 100 subjects. While this provided 900 jumps for potential analysis, 29 jumps (3%) were eliminated because of obviously improper landings (i.e. not landing on the force platform, landing with one foot first, etc.). For the remaining 871 jumps, there was (as should be expected) a significant ($p < 0.001$) correlation of 0.906 between the criterion jump heights and the air time predictions.

However, a paired samples t-test showed a significant ($p < 0.001$) mean difference, with the air time predictions averaging 0.015 meters higher (i.e. 5% higher than the criterion jumps). This supports the notion that subjects tend to land with their centres of mass slightly lower than they had been at take-off. Figure 4.21 (below) shows a scatterplot of these two variables, while table 4.12 (also below) provides a regression equation for predicting criterion jump heights from time in the air. This equation may be of some use in field studies, where timing mats are sometimes used to estimate 'real' jump heights from flight time in the air. It should be noted that the standard error of estimate in predicting criterion jump heights from air time was found to be 11% of the mean criterion jump height - a substantial amount of error if individual scores, rather than group means, are of importance. It may be that some subjects land with a greater degree of joint flexion than others, although a kinematic study would be required to prove this.

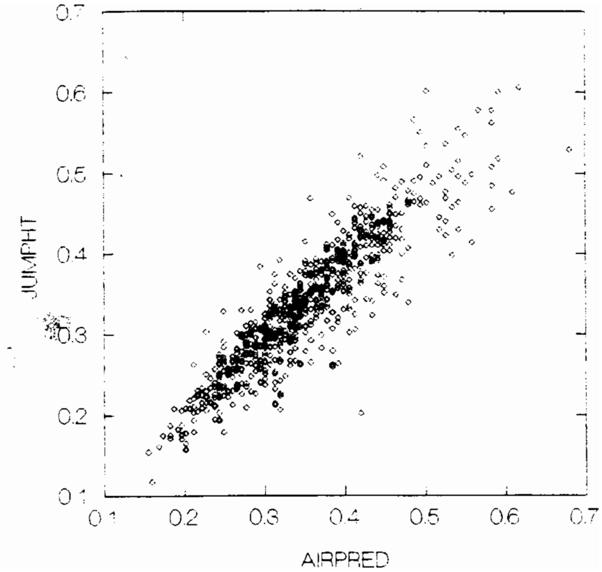

Figure 4.21: Scatterplot of Criterion Jump Heights Versus Air Time Predictions.

EQUATION	R	STANDARD ERROR OF ESTIMATE	S.E.E. AS PERCENT OF MEAN
JHT = -0.279 + (1.155 AIRTIME)	0.906	0.036	11 %

Table 4.12: Regression Equation For Predicting Criterion Jump Height From Air Time in Seconds.

Gender and the Jumps:

As expected, the males jumped higher than the females for all three types of jumps. Figure 4.22 (below) shows box-and-whiskers plots for males and females in the static jump. (The centre horizontal line is the median, while the hinges or edges of the central box split each half in half again; see Tukey (1977), Velleman and Hoaglin (1981), and Wilkinson et al. (1992)). The other two jumps had similar differences. However, the assumption made in the modelling approach is that this difference could be accounted for by the structural differences between the males and females, and that a single anthropometric model for predicting vertical jumps should work for both genders. This assumption was checked with the final models, and is reported later in this chapter.

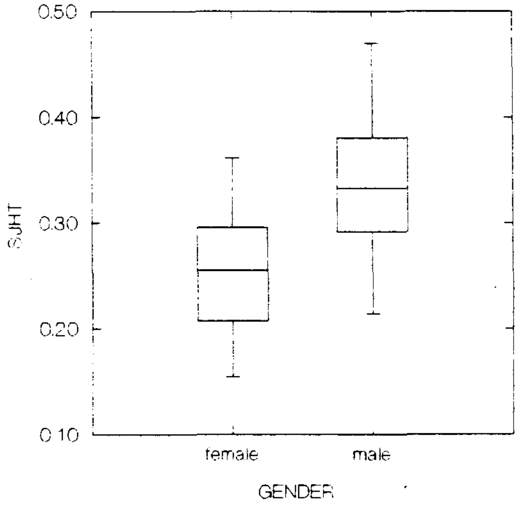

Figure 4.22: Box-and-Whiskers Plots for Gender and Static Jump Height (m).

Sport and the Jumps:

Figure 4.23 (below) shows box-and-whiskers plots for the various sports from which the subjects in this research came. Sport differences were not an important aspect of this study, however, and the small numbers from each sport, and the lack of representative sampling, precludes firm generalizations about sport differences and jumping ability.

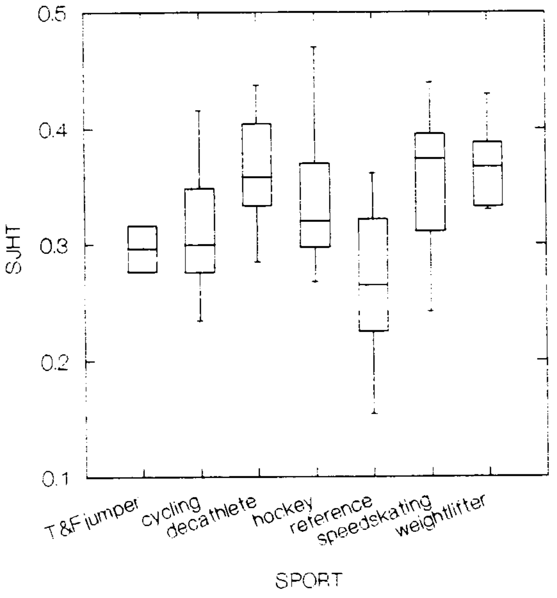

Figure 4.23: Box-and-Whiskers Plots for Sport and Static Jump Height (m).

Data overview:

In order to become familiar with the data, and to develop a good overall perspective of the relationships between all anthropometric variables and the jumps, a large matrix of Pearson correlation coefficients was produced, and is found in the three tables below. These tables include all the directly measured and derived anthropometric variables listed in Chapter III, as well as the additional derived variables required by the anthropometric analogue proposed near the end of Chapter III: e.g. (muscle girths)^2, and (estimated muscle mass)$^{2.3}$.

Table 4.13 shows the Pearson correlations of mass, lengths, and breadths with the three types of vertical jumps. Following this is a similar table with girths and corrected girths (table 4.14), and another with skinfolds, shape, and composition variables (table 4.15). Inspection of these rather large correlation matrices reveals obvious multicolinearity among the anthropometric variables.

ANTHROPOMETRY (Direct and Derived Variables)	STATIC JUMP	COUNTER JUMP	REACH JUMP
Age	-0.175	-0.135	-0.131
Mass	0.323	0.352	0.293
Stature	0.313	0.297	0.252
Stature Z	-0.128	-0.210	-0.175
Sitting Height	0.366	0.364	0.317
Sitting Height Z	-0.102	-0.161	-0.122
Arm Span	0.363	0.407	0.353
Arm Span Z	0.060	0.088	0.091
Upper Arm Length	0.248	0.301	0.264
Upper Arm Length Z	-0.097	-0.050	-0.027
Forearm Length	0.354	0.372	0.337
Forearm Length Z	0.115	0.107	0.130
Hand Length	0.409	0.483	0.456
Hand Length Z	0.159	0.241	0.280
Spinale Height	0.244	0.246	0.198
Trochanterion Height	0.287	0.258	0.224
Thigh Length	0.224	0.182	0.176
Thigh Length Z	-0.109	-0.195	-0.135
Tibiale Laterale Height	0.307	0.299	0.239
Tibiale Laterale Height Z	0.004	-0.053	-0.065
Leg Length	0.159	0.141	0.093
Foot Length	0.332	0.356	0.350
Foot Length Z	0.093	0.100	0.175
A-P Chest Depth	0.280	0.317	0.281
A-P Chest Depth Z	-0.079	-0.047	-0.062
Transverse Chest Breadth	0.329	0.395	0.330
Transverse Chest Breadth Z	0.148	0.244	0.202
Biacromial Breadth	0.396	0.456	0.445
Biacromial Breadth Z	0.117	0.175	0.230
Biiliocristal Breadth	0.034	0.001	0.002
Biiliocristal Breadth Z	-0.368	-0.437	-0.372
Humerus Breadth	0.462	0.480	0.422
Humerus Breadth Z	0.321	0.312	0.294
Wrist Breadth	0.517	0.512	0.468
Hand Breadth	0.504	0.571	0.523
Femur Breadth	0.369	0.396	0.356
Femur Breadth Z	0.128	0.130	0.152

Table 4.13: Pearson Correlations of Mass, Lengths, and Breadths with Vertical Jumps.

ANTHROPOMETRY (Direct and Derived Variables)	STATIC JUMP	COUNTER JUMP	REACH JUMP
Head Girth	0.270	0.328	0.257
Head Girth Z	-0.265	-0.269	-0.240
Neck Girth	0.494	0.519	0.494
Neck Girth Z	0.458	0.463	0.486
Arm Relaxed Girth	0.375	0.422	0.376
Arm Relaxed Girth Squared	0.367	0.415	0.368
Arm Relaxed Girth Z	0.326	0.376	0.355
Arm Flexed Girth	0.434	0.483	0.436
Arm Flexed Girth Squared	0.424	0.473	0.425
Arm Flexed Girth Z	0.438	0.493	0.467
Forearm Girth	0.466	0.521	0.467
Forearm Girth Squared	0.456	0.512	0.458
Forearm Girth Z	0.481	0.547	0.519
Wrist Girth	0.466	0.476	0.414
Wrist Girth Squared	0.458	0.468	0.405
Wrist Girth Z	0.370	0.346	0.317
Chest Girth	0.400	0.452	0.413
Chest Girth Squared	0.389	0.439	0.399
Chest Girth Z	0.348	0.416	0.425
Waist Girth	0.271	0.342	0.284
Waist Girth Squared	0.256	0.323	0.265
Waist Girth Z	0.143	0.249	0.204
Gluteal Girth	0.110	0.100	0.068
Gluteal Girth Squared	0.107	0.095	0.063
Gluteal Girth Z	-0.473	-0.540	-0.487
Thigh Girth	0.110	0.125	0.060
Thigh Girth Squared	0.111	0.124	0.060
Thigh Girth Z	-0.309	-0.329	-0.358
Mid-Thigh Girth	0.322	0.345	0.275
Corrected Mid-Thigh Girth	0.536	0.591	0.506
Corrected Mid-Thigh Girth Squared	0.533	0.590	0.502
Calf Girth	0.140	0.151	0.087
Corrected Calf Girth	0.379	0.413	0.337
Corrected Calf Girth Squared	0.370	0.402	0.323
Calf Girth Z	-0.289	-0.307	-0.326
Ankle Girth	0.216	0.207	0.171
Ankle Girth Squared	0.212	0.202	0.166
Ankle Girth Z	-0.163	-0.223	-0.196

Table 4.14: Pearson Correlations of Girths and Corrected Girths with Vertical Jumps.

ANTHROPOMETRY (Direct and Derived Variables)	STATIC JUMP	COUNTER JUMP	REACH JUMP
Triceps Skinfold	-0.454	-0.509	-0.485
Triceps Skinfold Z	-0.506	-0.564	-0.534
Subscapular Skinfold	-0.236	-0.228	-0.224
Subscapular Skinfold Z	-0.301	-0.297	-0.283
Biceps Skinfold	-0.330	-0.413	-0.396
Biceps Skinfold Z	-0.373	-0.462	-0.438
Iliac Crest Skinfold	-0.215	-0.214	-0.179
Iliac Crest Z	-0.274	-0.276	-0.231
Supraspinale Skinfold	-0.244	-0.270	-0.256
Supraspinale Skinfold Z	-0.307	-0.338	-0.316
Abdominal Skinfold	-0.331	-0.330	-0.289
Abdominal Skinfold Z	-0.392	-0.393	-0.343
Front Thigh Skinfold	-0.447	-0.522	-0.479
Front Thigh Skinfold Z	-0.477	-0.553	-0.506
Medial Calf Skinfold	-0.448	-0.485	-0.460
Medial Calf Skinfold Z	-0.494	-0.535	-0.503
Sum Of (Eight) Skinfolds (SOS)	-0.379	-0.414	-0.381
Mass-Adjusted Sum of Skinfolds (SOS$_w$)	-0.530	-0.530	-0.524
Log$_{(10)}$ SOS$_w$	-0.559	-0.559	-0.506
Angularity Index of Thigh	0.018	0.074	0.003
Angularity Index of Shank (Leg)	0.058	0.025	-0.012
Proximorphy Index of Lower Extremity	0.503	0.555	0.494
Crural Index	0.145	0.196	0.100
Endomorphy	-0.412	-0.428	-0.400
Mesomorphy	0.367	0.443	0.398
Ectomorphy	-0.132	-0.216	-0.181
Kerr Estimate of Skin Mass	0.335	0.350	0.294
Kerr Estimate of Adipose Mass	-0.257	-0.294	-0.280
Kerr Estimate of Muscle Mass	0.486	0.546	0.484
% Muscle Mass (from Kerr Estimate)	0.462	0.536	0.516
(Kerr Estimate of Muscle Mass)$^{2/3}$	0.491	0.552	0.490
Kerr Estimate of Bone Mass	0.371	0.403	0.372
Kerr Estimate of Residual Mass	0.394	0.443	0.373

Table 4.15: Pearson Correlations of Skinfolds, Shape, and Composition Variables with Vertical Jumps.

Anthropometric Variable Reduction:

The large number of anthropometric variables were narrowed down to a much smaller number of candidate variables as a result of three different processes:

1. analysis of the above correlation coefficients with the jumps;
2. principal components analyses;
3. theoretical and practical considerations.

CORRELATION COEFFICIENTS (ANTHROPOMETRY VERSUS THE JUMPS):

It should be noted that *none* of the correlations between the anthropometry and the vertical jumps was very high. The best positive correlation was 0.591, between corrected mid-thigh girth and the counter movement jump, while the largest negative correlation was -0.564, between the triceps skinfold and the counter movement jump. No single variable explained more than 35% of the variance in a jump height.

However, while the correlations were low, the patterns were very consistent and, with the reasonably large numbers (n = 88 for the static jump and 91 for the counter movement and reach jumps), many of the correlations were shown to be significant by Bonferroni-adjusted probabilities. The main difficulty was due to the omnipresent multicolinearity, and the objective was to reduce the large number of variables to those that were not only usefully predictive, but also likely to be explanatory. Much of this process was simply common sense.

A number of points can be made from a largely subjective assessment of the correlation coefficients.

Mass had a low but significant ($p < .05$) positive correlation with all three jumps. This is likely to have been sample-specific, though, as one can imagine samples where this would not be the case. Dowling and Vamos (1993, p. 104) revealed a similar finding, and stated:

> "this does not mean that increased weight causes higher jumps but rather that in the present sample, the larger subjects were probably more muscular and therefore had a tendency to be able to jump higher."

While there was no significant correlation here between mass and percent muscle mass (from the Kerr tissue estimates), there were significant correlations between mass and all skinfold adjusted 'muscle' girths, and, more important, between mass and the upper body girth Z scores and mass and mesomorphy. The larger subjects in this study were the highly trained decathletes and weight lifters, who were also good jumpers.

Many other size variables may have had similar correlations with the jump height, by virtue of being correlated with mass. This phenomenon almost certainly explains the low but often significant correlations between the breadths and the jump heights, since there is no good reason to believe that greater breadths, by themselves, had any direct causative influence on jump heights.

Stature had low but significant ($p < 0.05$) positive correlations with static and counter movement jumps (not with the reach jump). However, the stature Z-scores, which are mass-adjusted, actually have negative (albeit insignificant) correlations with all three jumps. In other words, stature, and quite likely all the other length measurements, are only positively correlated with the jumps because they are also correlated with mass and (in this sample) with muscularity.

Equation 44, which served as the basis for the anthropometric analogue and is repeated here for convenience, includes a length term which stressed the advantage of a longer distance through which one can apply forces; i.e. an acceleration distance, or work distance.

$$h = F \times \frac{1}{m} \times d \times \frac{1}{g} \tag{Eq. 44}$$

The lack of a strong relationship here between anthropometric lengths (including stature) and the jump heights suggests one of two things:

1. differences in lengths within the human species are of so little relative consequence that they are obscured by other more important differences, and/or;

2. individuals may achieve greater acceleration distances simply by dropping lower in a counter movement, or starting at a lower squat position in the static jump.

All of the skinfolds *and* the skinfold z-scores had significant negative correlations with the jump heights. There are probably two reasons for this - one direct and the other indirect:

1. adiposity is "dead" weight that has to be accelerated upwards, yet it produces none of the forces to do this (the direct cause), and;

2. increased adiposity is related to a sedentary lifestyle which is unlikely to produce good jumpers, and is not usually found in large quantities on the fit and strong (the indirect cause).

It should be noted that all skinfold Z-scores were even more highly negatively correlated with jump heights than were the raw scores. If you're a jumper, it's bad to be fat, but it's worse to be proportionally fat!

As far as the propulsive tissue is concerned, all the muscle girth raw scores were positively correlated with the jumps, but unlike the lengths and breadths, most of the girth Z scores maintained the pattern of positive correlations with the jumps (i.e. mass was effectively held constant by the z-scores).

The girth measurements actually reflect varying proportions of muscular area within their perimeters. At one extreme, the head girth is almost entirely a measure of skull size, with no real muscle mass present. Wrist and ankle girths also reflect bone size as much if not more than muscle and tendon. Substantial muscle mass is encompassed by the chest, waist and gluteal girths, but there are many other structures also present in those areas.

The extremity girths are likely to contain the highest proportion of muscle cross-sectional area. Among all the girths, forearm girth and mid-thigh girth appear to have had the highest relationships with the jumps.

It can be seen that providing a skinfold correction to the mid-thigh girths (according to equation 42, p. 135) substantially improved the correlation with the jumps. (This gave some credance to the skinfold-correction technique used!) The forearm did not need a skinfold correction since there is normally so little subcutaneous adipose tissue in that area.

Gluteal and upper thigh girth z-scores were actually negatively correlated with the jumps. Again, these were not skinfold corrected girths, and among females and sedentary males, they may include considerable amounts of fat. This effect was also seen with the calf girths, where the low positive correlations between the girth raw scores and the jump heights became negative for the calf girth z-scores. When skinfold corrected, the raw scores become more positively correlated with the jumps.

Many body builders have vented their frustration with the difficulty they encounter attempting to achieve calf hypertrophy. This area does not appear to respond to strength training with size increases to the extent that the thigh and other areas do. Strength-trained athletes may achieve proportionally much greater girth increases at the thigh than in the calf. This would result in a greater differential between the skinfold-corrected mid-thigh girth and the skinfold-corrected calf girth, and a greater proximorphic index. Indeed, the proximorphic index had relatively high and significant ($p < 0.001$) correlations with the jumps. Again, there were two possible reasons for the relationship:

1. as mentioned above, strength training may increase thigh girths proportionately more than the calf girths, and since the strength training is likely to improve jumping ability, there is a potential indirect effect;
2. there may be a mechanical advantage (e.g. smaller moments of inertia around the hip and knee joints) in having a proximorphic shape similar to what is seen in the animal world; i.e. a potential direct effect.

Neither of the angularity indices had significant correlations with the jumps, nor did the crural index, but endomorphy was significantly negatively correlated ($p < 0.001$) while mesomorphy was significantly positively correlated with all of them ($p < 0.01$). This should not be surprising, since the endomorphy is based on skinfolds and the mesomorphy is based on girths and breadths.

Finally, the Kerr estimate of muscle mass shows reasonably good correlations with the jumps (i.e. higher than total mass or any of the other tissue masses). Interestingly, the correlation is ever-so-slightly improved by taking it to the 2/3 power, thereby making it dimensionally consistent with the girths. Dividing the Kerr estimate of muscle mass by total body mass (to get an estimate of percent muscle mass) also provides comparatively good correlations with the jumps.

PRINCIPAL COMPONENTS ANALYSIS:

Wilkinson et al. (1992) note that the principal component analysis was developed by Karl Pearson in 1901, who described it as a "line of closest fit to systems of points in space." The goal of a principal components analysis is:

> "to summarize a multivariate dataset as accurately as possible using a few components.... The first component will summarize as much of the joint variation as possible. The second will summarize what's left...."
>
> (Wilkinson et al., 1992, p. 100)

In other words, an attempt is made to maximize the reduction of variables to as few components as possible, while still explaining most of the variance. It differs somewhat from factor analysis, as is described below.

> "Principal components are weighted linear composites of observed variables (whereas) common factors (derived from factor analysis) are unobserved variables that are hypothesized to account for the intercorrelations among observed variables."
>
> (Wilkinson et al., 1992, p. 101)

Principal components analyses were used here to test some of the interpretations of the correlations described above, to determine colinearity among the many variables, and to help choose the final candidate variables for the models. All the measured variables were factored into a limit of four groups, although the first factor explained 41% of the variance (see Appendix B). Virtually all of the variables but the skinfolds loaded high on this first factor, with mass the highest. This confirmed the high colinearity most of the variables had with mass.

The second factor explained another 23% of the variance, and was dominated by the skinfolds, while the third and fourth factors together only explained 15%, and did not have many primary members (i.e. variables more related to that factor than to any other).

The third component included the positive loadings of a number of lengths and negative loadings of most girths and breadths. This suggested that the third component was related to linearity (i.e. a 'stretched-out' physique). As a check on this, ectomorphy did load high on this component (0.545), while mesomorphy ('musculo-skeletal robustness') loaded negatively (-0.619).

The fourth component seemed to be loaded positively with upper body size measures, especially skinfolds. In fact, endomorphy was relatively positively loaded (0.233) while thigh and calf girth (raw and z-scores), and angularity of the thigh and shank, had the highest negative loadings.

The four components together accounted for approximately 80% of the total variance.

To summarize, the principal components analysis confirmed the subjective assessment of the correlations. This was a classic example of a redundant data set!

THEORETICAL AND PRACTICAL CONSIDERATIONS:

Table 3.8 (p. 157) was re-vistited, with a view to modifying the candidate variables. *Work distance* was left out as a category, for the reasons described above. Total weight was not used for the *mass accelerated* category, since total weight (mass) was so highly colinear with everything else. The skinfold measurements, endomorphy, and adipose weight seemed like a good bet for this, especially since they formed a very distinct second component in the principal components analysis.

Effective Force Production		**Mass Accelerated**	**Work Distance**
Force Generation (Muscle Girths Squared)	Force Application (Shape Characteristics)	Total Weight or "Dead" Weight	(For Force Application)
Candidate Variables			
corr. mid-thigh girth^2 forearm girth Z muscle mass$^{2/3}$	proximorphy mesomorphy	log$_{(10)}$ SOS$_W$ triceps skinfold Z adipose weight	DELETED

Table 4.16: Revised Candidate Variables for Anthropometric Analogue.

The question became, which adiposity measure should be used? The triceps had the single highest negative correlation with the jumps, its phantom z-score dissociates mass and avoids the colinearity problem, and being a single predictive measure it had the appeal of simplicity and efficiency. However, individual predictive ability (not just that for groups) is desirable here, and skinfold patterning shows considerable individual differences (e.g. as with dysplasias) as well as gender differences. For this reason, a predictor more robust to skinfold patterning differences is likely to be the sum of eight skinfolds (herein mass adjusted and transformed to $\log_{(10)}$) since it includes skinfold sites from all body segments. This had negative correlations with the jumps (SJ = -0.559, CJ = -0.559, RJ = -0.506), about equal to those of the triceps z-scores (SJ = -0.506, CJ = -0.564, RJ = -0.534).

Finally, the effective force production category required a muscle component and a dimensionless shape variable. It was clear that corrected mid-thigh girth (SJ = 0.536, CJ = 0.591, RJ = 0.506), and, for dimensional consistency, its squared counterpart (SJ = 0.533, CJ = 0.590, RJ = 0.502), had by far the highest relationship to the jumps among all the individual girths. A reasonable backup choice for single measurement prediction was the forearm girth Z-score. The Kerr estimate of muscle mass [2,3] (which should be proportional to the cross-sectional areas of the muscle mass) had the following correlations with the jumps; SJ = 0.491, CJ = 0.552, RJ = 0.490. The percent muscle mass (also from the Kerr estimate) was similarly correlated with the jumps; SJ = 0.462, CJ = 0.536, RJ = 0.516.

Several indices were made to reflect the ‘force/mass’ ratio $[L^{-1}]$ that is part of the physics equation being mimicked. For example, the Kerr estimate of muscle mass [2,3] $[L^2]$ was divided by total body mass $[L^3]$, but the resulting index had poor (insignificant) correlations with the jumps (SJ = 0.097, CJ = 0.131, RJ = 0.158). The same thing occurred with several other similar indices which were created. Again, this is likely to be due to the high degree of colinearity between muscle mass and total body mass.

From among the shape variables, a relatively high correlation was found between lower extremity proximorphy and the three jumps (SJ = 0.503, CJ = 0.555, RJ = 0.494). Leaving out endomorphy, which was highly correlated with the $\log_{(10)}$ mass-adjusted sum of eight skinfolds in the 'dead weight' category, the next best shape relationship with the jumps came from mesomorphy (SJ = 0.367, CJ = 0.443, RJ = 0.398).

Model Determination:

Single variable and multiple regressions were produced. The revised candidate variables from Table 4.16 (above) were first forced into the equations. Criteria for selection were:

1. theoretical soundness of the mix of variables included;
2. high multiple correlation coefficients;
3. low standard errors of estimate;
4. significance (set at $p < 0.05$) of the component variables within the multiple regression equation. (Wilkinson et al. (1992) recommend that T values for variables exceed 2.0);
5. tolerance (a measure of the colinearity of the independent variables) set at a minimum of 0.1 (according to the guidelines suggested by Wilkinson et al. (1992)).

In the final models selected, the T statistic for each variable was always greater than 3.0, while the minimal tolerance always exceeded 0.6.

To confirm the model selection, all the candidate variables were entered into an automatic backwards-stepping procedure, whereby insignificant and/or highly colinear variables were successively deleted. This procedure yielded the same results as the initial interactive method, in which the leading candidate variables were forced to participate.

The Anthropometric Jump Models:

EQUATION	MULTIPLE R	STANDARD ERROR OF ESTIMATE	S.E.E. AS PERCENT OF MEAN
STATIC JUMP Mean = 0.312 S.D. = 0.068			
$SJHT = 0.410671 + (0.009290\ PROXIMORPHY) + (-0.168521\ LOGSOS_W)$	0.649	0.053	17.0 %
$SJHT = 0.406254 + (0.000044\ CORMIDTHG)^2 + (-0.145481\ LOGSOS_W)$	0.616	0.054	17.3 %
COUNTER JUMP Mean = 0.340 S.D. = 0.069			
$CJHT = 0.432762 + (0.010280\ PROXIMORPHY) + (-0.174825\ LOGSOS_W)$	0.699	0.050	14.7 %
$CJHT = 0.406488 + (0.000053\ CORMIDTHG)^2 + (-0.142546\ LOGSOS_W)$	0.663	0.052	15.3 %
REACH JUMP Mean = 0.395 S.D. = 0.089			
$RJHT = 0.491699 + (0.011947\ PROXIMORPHY) + (-0.195079\ LOGSOS_W)$	0.615	0.071	18.0 %
$RJHT = 0.484677 + (0.000057\ CORMIDTHG)^2 + (-0.165457\ LOGSOS_W)$	0.571	0.074	18.7 %

Table 4.17: The Anthropometric Jump Models.

The anthropometric jump models are summarized in Table 4.17 above. A primary model was chosen for each jump, and a second choice chosen as a "backup".

For all three jumps, the *proximorphic index* and the *log of the mass-adjusted sum of 8 skinfolds* came up as significant, even when all other candidate variables were included simultaneously and found non-significant. In a backwards stepping procedure, forearm girth z scores were the last to be dropped off the equation for the final models for each jump type.

The Performance of the Models:

The proportion of the variability in jump heights which was explained by the two chosen models for each jump type is given in standard deviation units by the *multiple r*, and it ranges from 0.57 to 0.70. The first model predicted the counter jump best (SEE% = 14.7%), and the reach jump worst (SEE% = 18.0%). Re-inspection of table 4.10 shows that each jump height can be better predicted from a knowledge of the height obtained by the other jump types than from the anthropometry, but this is to be expected, since predicting one performance from a similar one should be much more precise than predicting that performance from measures of structure.

Highly significant and consistent patterns were found from among the anthropometric predictors, and the standard error of estimate (analagous to the technical error of measurement) was lowered substantially from a simple guess at the mean for the group. Leverage, which is the effect that outliers have in the independent variable space, was below the 0.2 safety level advocated by Wilkinson et al. (1992) for all six models. The highest first order autocorrelation was 0.079, indicating no systematic trend of the residuals. Figure 4.24 (below) shows the plot of the residuals for the counter movement jump versus the predicted values, and, as with similar plots for the other jumps, no remaining trend is observed. Figures 4.25 and 4.26 show the plots of the residuals for the counter movement jump against the two anthropometric predictors: the proximorphy index and the $\log_{(10)}$ mass-adjusted sum of skinfolds.

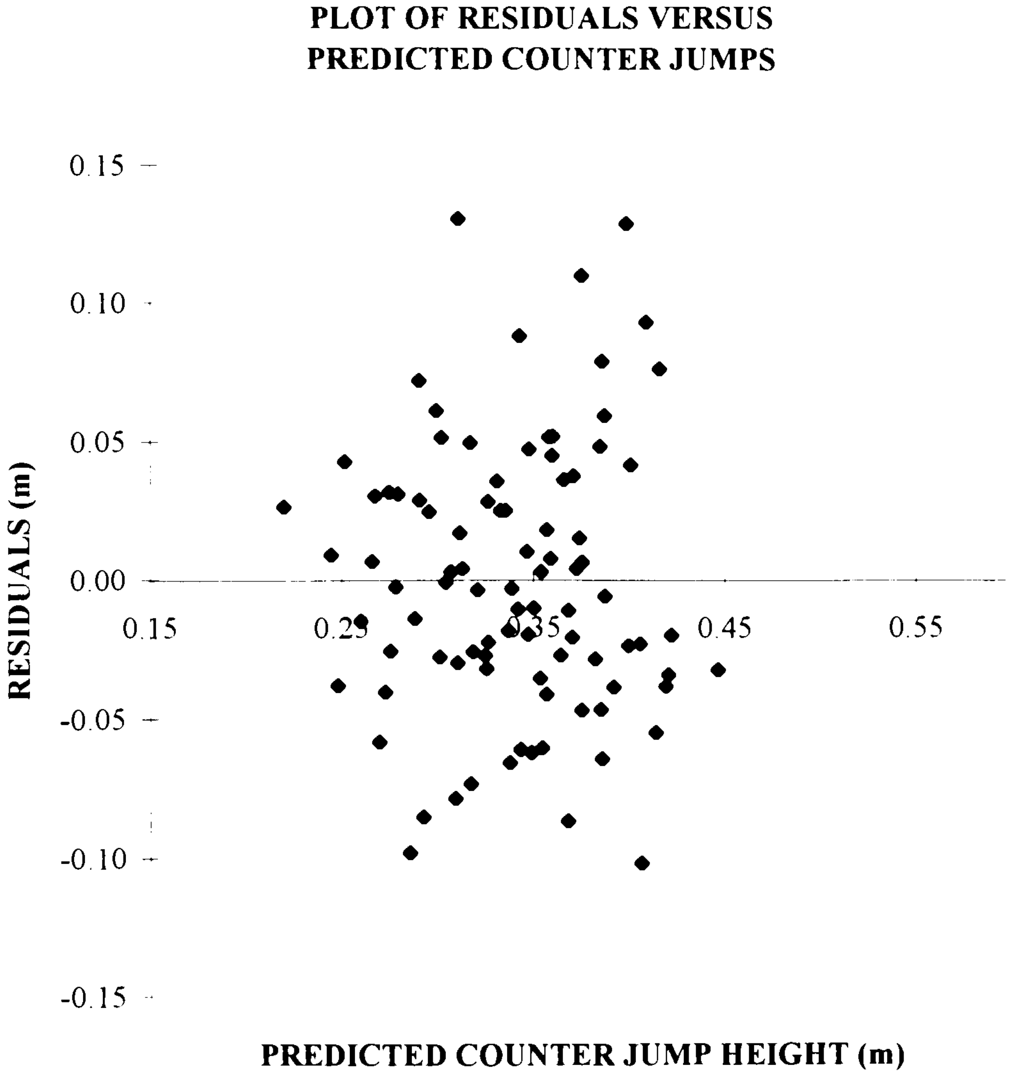

Fig. 4.24: Plot of Residuals (Predicted Minus Actual Jump Heights) Versus Predicted Counter Jumps.

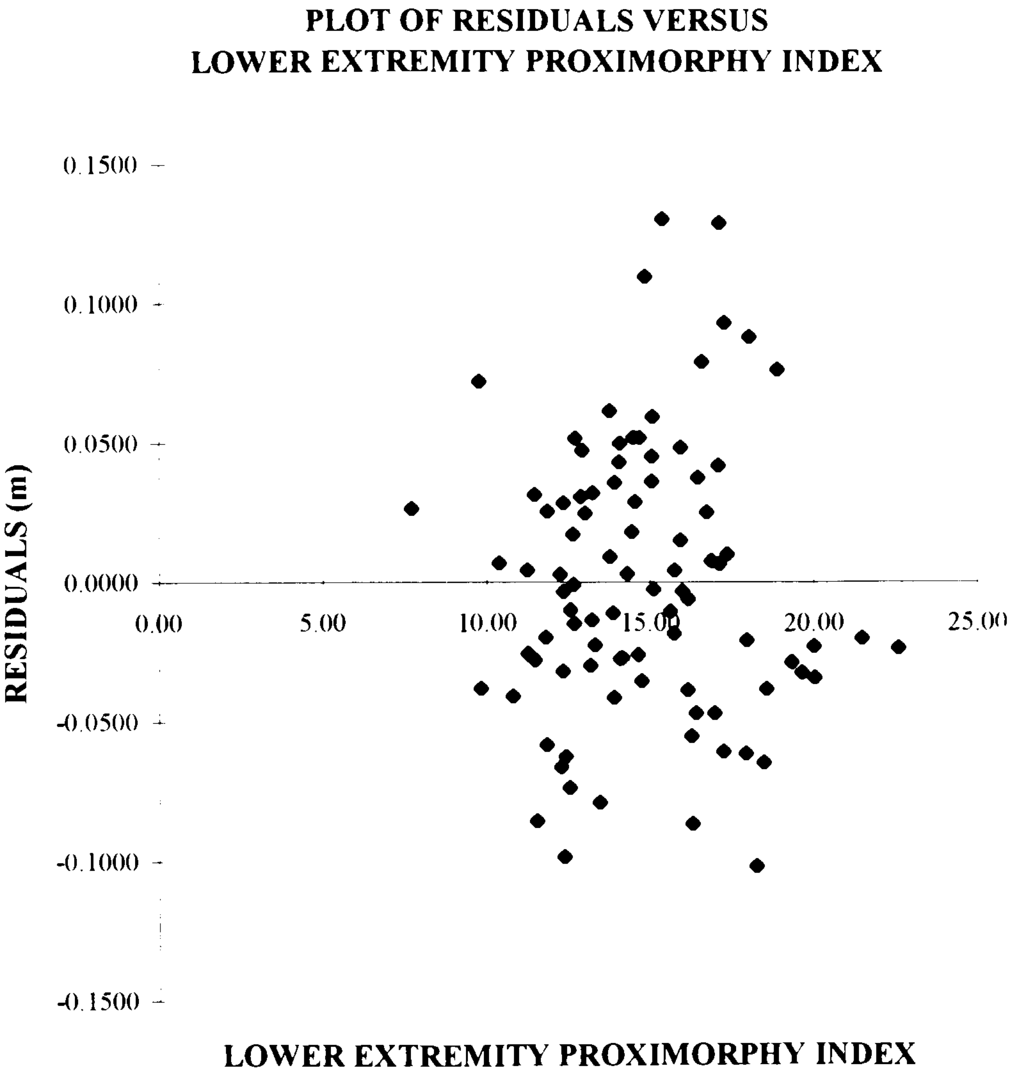

Fig. 4.25: Plot of Residuals (Predicted Minus Actual Jump Heights) Versus the Lower Extremity Proximorphy Index.

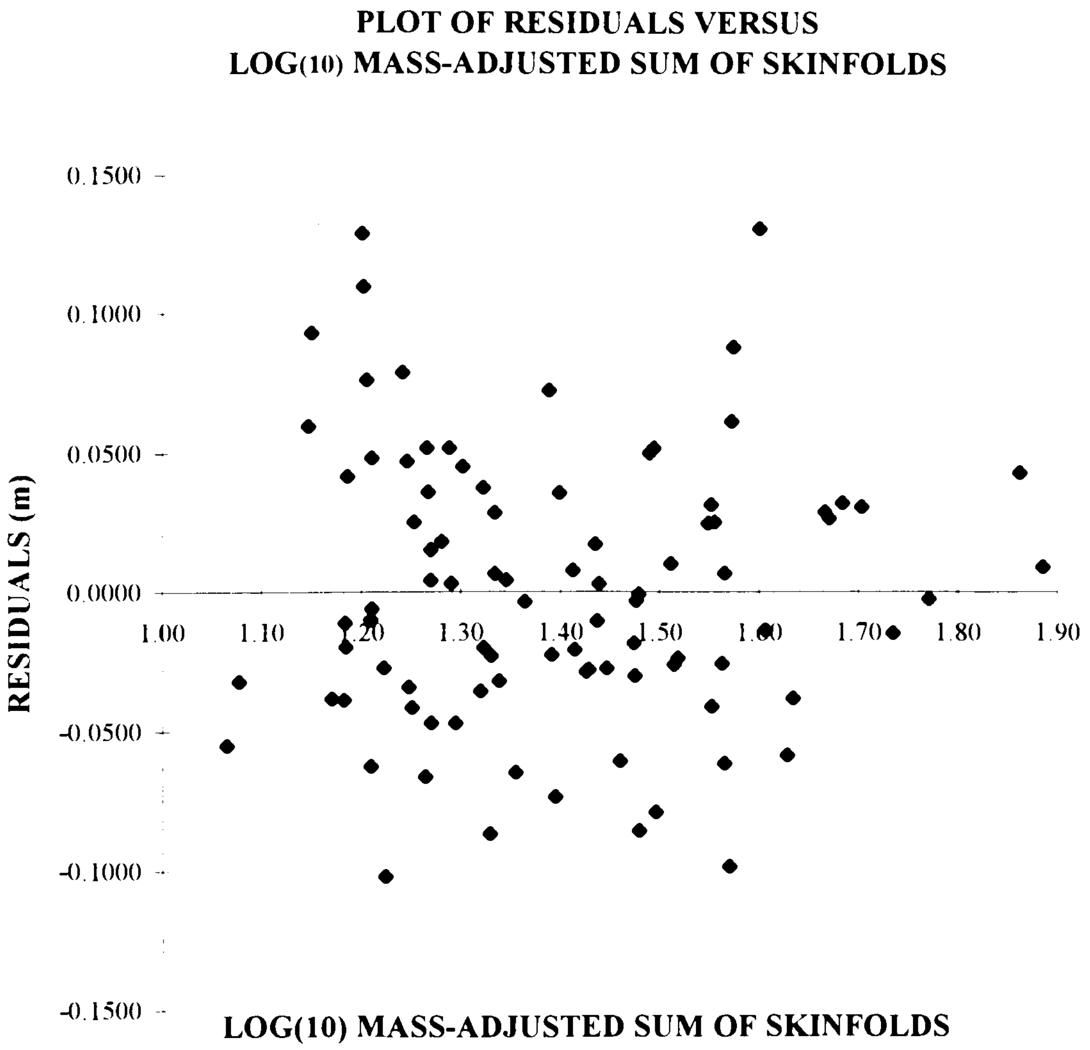

Fig. 4.26: Plot of Residuals (Predicted Minus Actual Jump Heights) Versus the Log(10) Mass-Adjusted Sum of Skinfolds.

The modelling process assumed that gender differences in jump heights could be accounted for by structure alone, and aimed for a unisex model based on anthropometry, which would avoid the necessity of having separate male and female models. To test the validity of this assumption, the residuals were analyzed by gender, as described by table 4.18 (below). A small bias was evident, with the predictions for males slightly underestimating actual jump heights, and those for females slightly overestimating them. This trend suggests that gender may not be completely explained by anthropometric differences. However, the differences in male and female residuals were not statistically significant, and the prospects for unisex, anthropometry-based jumping models were generally supported.

STATISTICS ON RESIDUALS BY GENDER	**MALES**	**FEMALES**
STATIC JUMP		
N	64	24
MEAN ABSOLUTE ERROR (Error Magnitude) (m)	0.0408	0.0444
MEAN CONSTANT ERROR (Error Bias) (m)	-0.0035	0.0094
STANDARD DEVIATION (m)	0.0504	0.0561
COUNTER MOVEMENT JUMP		
N	65	26
MEAN ABSOLUTE ERROR (Error Magnitude) (m)	0.0408	0.0358
MEAN CONSTANT ERROR (Error Bias) (m)	-0.0031	0.0077
STANDARD DEVIATION (m)	0.0506	0.0454
REACH JUMP		
N	65	26
MEAN ABSOLUTE ERROR (Error Magnitude) (m)	0.0593	0.0452
MEAN CONSTANT ERROR (Error Bias) (m)	-0.0061	0.0153
STANDARD DEVIATION (m)	0.0752	0.0535

Table 4.18: Statistics on Residuals By Gender.

Testing of the Models on a Sample of Hockey Players:

The hockey study provided a sample of 68 elite male hockey players, ranging from semi-professional juniors to NHL players. As described above, they underwent identical anthropometry, and 51 performed the vertical jump protocols. The vertical jumps were performed on the portable force mat, however, and it was not possible to determine if there was a systematic difference between heights recorded on this equipment versus the force platform in the laboratory.

The best model for each jump (i.e. involving proximorphy and the log of the mass-adjusted sum of skinfolds) was applied to the hockey study data to yield predictions for the hockey players' jumps. Their actual jump heights were subtracted from their predicted heights, and the error scores (residuals) were plotted along with the predicted jumps. Figure 4.27 (below) shows the example from the counter movement jumps. (One outlier had a prediction .15 metres less than his actual jump.)

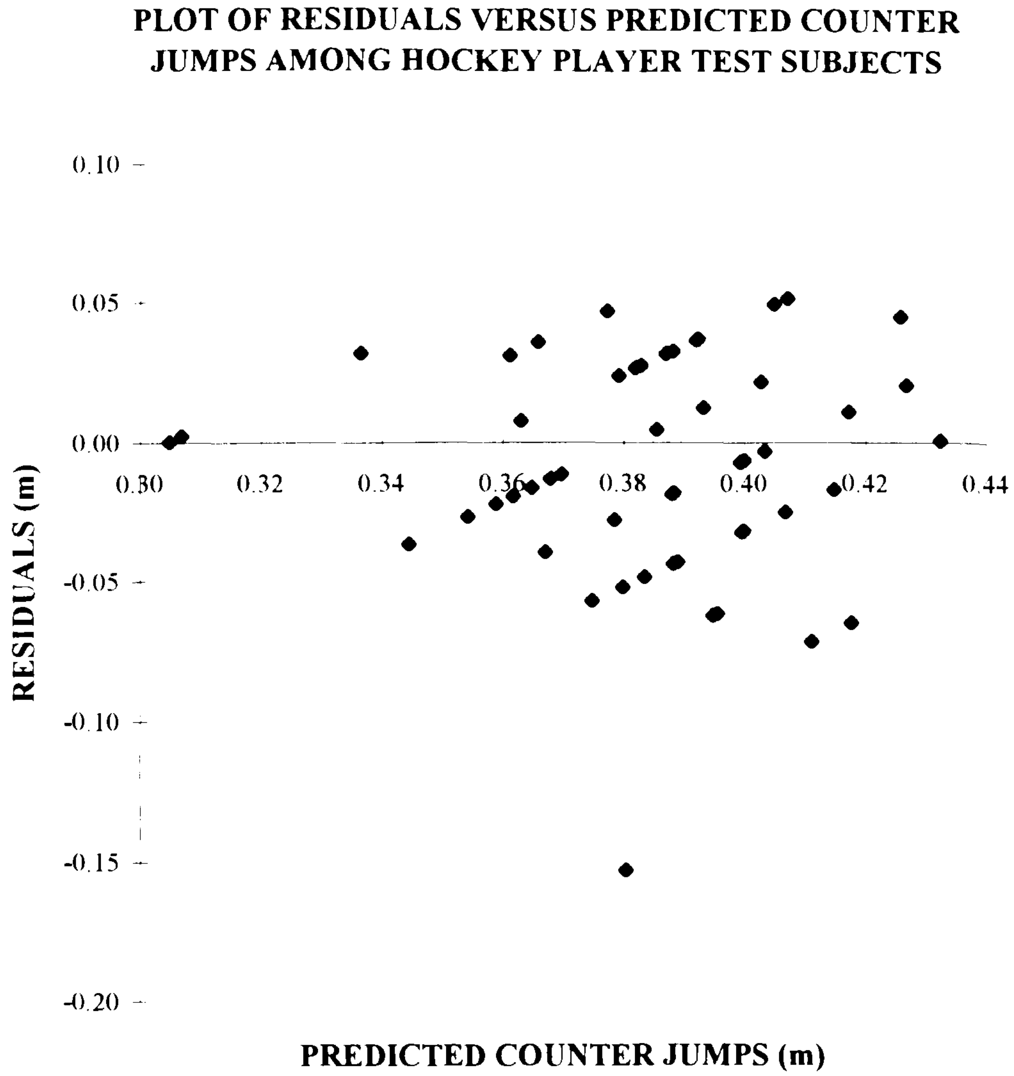
PLOT OF RESIDUALS VERSUS PREDICTED COUNTER JUMPS AMONG HOCKEY PLAYER TEST SUBJECTS

Fig. 4.27: Plot of Residuals (Predicted Minus Actual Jump Height) Versus Predicted Counter Jumps Among Hockey Player Test Subjects.

Table 4.19 (below) compares the means and standard deviations of the actual jump heights and the jump heights predicted from the models.

	STATIC JUMP		COUNTER JUMP		REACH JUMP	
N = 51	PREDICTED	ACTUAL	PREDICTED	ACTUAL	PREDICTED	ACTUAL
MEAN (m)	0.3536	0.3785	0.3843	0.3930	0.4456	0.4482
S.D. (m)	0.0246	0.0435	0.0262	0.0472	0.0297	0.0473

Table 4.19: Predicted and Actual Jump Heights in Hockey Study.

The only significant difference between predicted and actual jump heights occurred with the static jumps ($p < 0.001$). The hockey players exceeded the predicted values in the static jump by an average of about 2.5 cm. It is difficult to explain such a systematic difference for that jump when similar differences are not found with the other two jump types. It may be that hockey players are better trained to explode from a squat position. Certainly the accelerations required in skating involve the powerful hip extensions and gluteal activity that may help performance more in a static jump.

The fact that there was no significant difference between the predicted and actual jump heights for the counter movement and reach jumps supports (although doesn't prove) the assumption that there was no systematic difference between jumps heights measured by the force platform and the force mat.

Table 4.20 provides a summary of the descriptive statistics of the residuals, or error scores, that were formed by subtracting actual jump heights from predicted ones.

N = 51	STATIC JUMP	COUNTER JUMP	REACH JUMP
MEAN ABSOLUTE ERROR (Error Magnitude) (m)	0.0335	0.0316	0.0308
MEAN CONSTANT ERROR (Error Bias) (m)	-0.0249	-0.0087	-0.0027
S.D. (TEM) (m)	0.0335	0.0402	0.0382
% TEM	11.31%	10.23%	8.51%

Table 4.20: Descriptive Statistics of Residuals From Hockey Study.

The magnitude of the errors was quite small, and while there was a consistent negative bias of the predictions (the hockey players tended to exceed their predicted jump heights) it was only significant for the static jump. This trend towards under prediction of the hockey players may be explained by the fact that most were very fit professional athletes, whereas the major study sample (from which the model was derived) had many 'normal' subjects who likely had much lower levels of fitness. Again, anthropometry is unlikely to be able to describe all the changes that occur from prolonged, intense training.

The standard deviation of the residuals (equivalent to the technical error of measurement) was actually smaller than that for the sample in the major study upon which the models were based. As a result, the % TEM tested lower with the hockey players (8.51-11.31%) than with the original sample (14.7-18.0%). This was a surprise!

There are various techniques for testing a model, and many of them involve holding out a percentage of the sample upon which the model is based, in order that the model can genuinely be tested on different people, albeit from the same sample. In this particular study, proper sampling procedures could not be followed, and the sample cannot be said with any authority to be representative of any particular population. Because of this, it appeared to be important to test the model on a completely different group (although eight hockey players were also included in the major study). The model performed better on this test group than for the sample upon which it was based. It should be kept in mind, though, that the test sample of hockey players were more homogeneous than the original sample, and the decreased variability results in a bias.

Force-Time Curve Characteristics:

Dowling and Vamos (1993) studied kinetic and temporal factors related to vertical jump performance, and found that the large variability in the patterns of force application precluded the identification of criterion force-time curve characteristics of a good jump performance. A high maximum force (greater than twice body weight) was found to be "necessary but not sufficient" for a good performance, since some subjects had low jumps in spite of large peak forces.

Similar results were discovered here. Peak forces correlated rather poorly with jump heights, as is shown in table 4.21, and figures 4.28, 4.29, and 4.30 below. The correlation was poorest with the static jump, while once again the counter movement and reach jumps showed greater similarities. However, corrected mid-thigh girth^2 and, to a lesser extent proximorphy, had substantive correlations with the peak forces, as is shown by figures 4.31 and 4.32. It appears that structure can give a somewhat better prediction of the maximal forces generated in the jumps than of the jump heights themselves.

	STATIC JUMP PEAK FORCE	**COUNTER JUMP PEAK FORCE**	**REACH JUMP PEAK FORCE**
JUMP HEIGHT	0.386	0.537	0.543
CORR. MID-THIGH GIRTH^2	0.783	0.842	0.850
PROXIMORPHY	0.534	0.596	0.536
IMPULSE DEFICIT	N/A	0.794	0.740

Table 4.21: Correlates of Peak Forces.

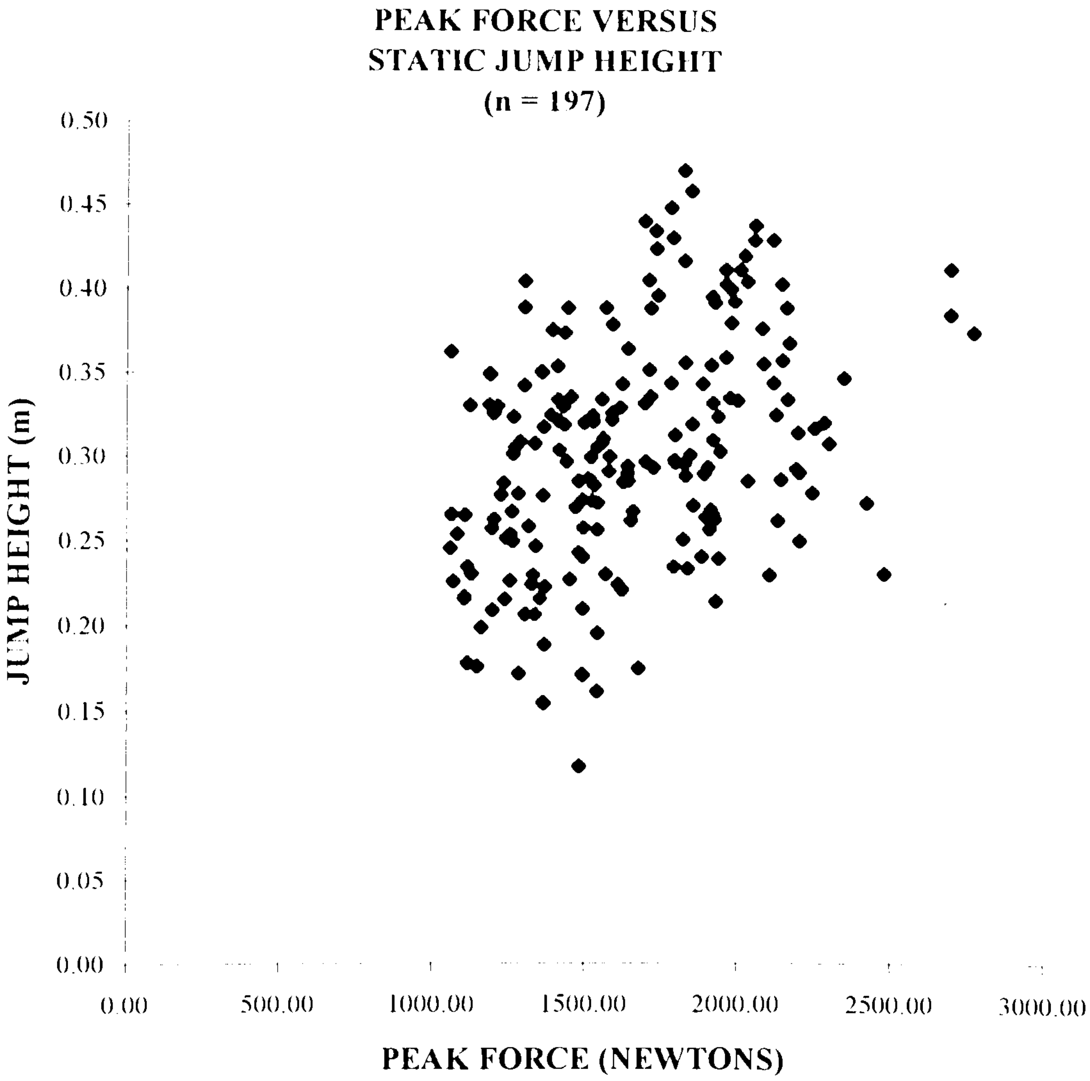

Fig. 4.28: Peak Force Versus Static Jump Height ($r = 0.386$, $p < 0.001$).

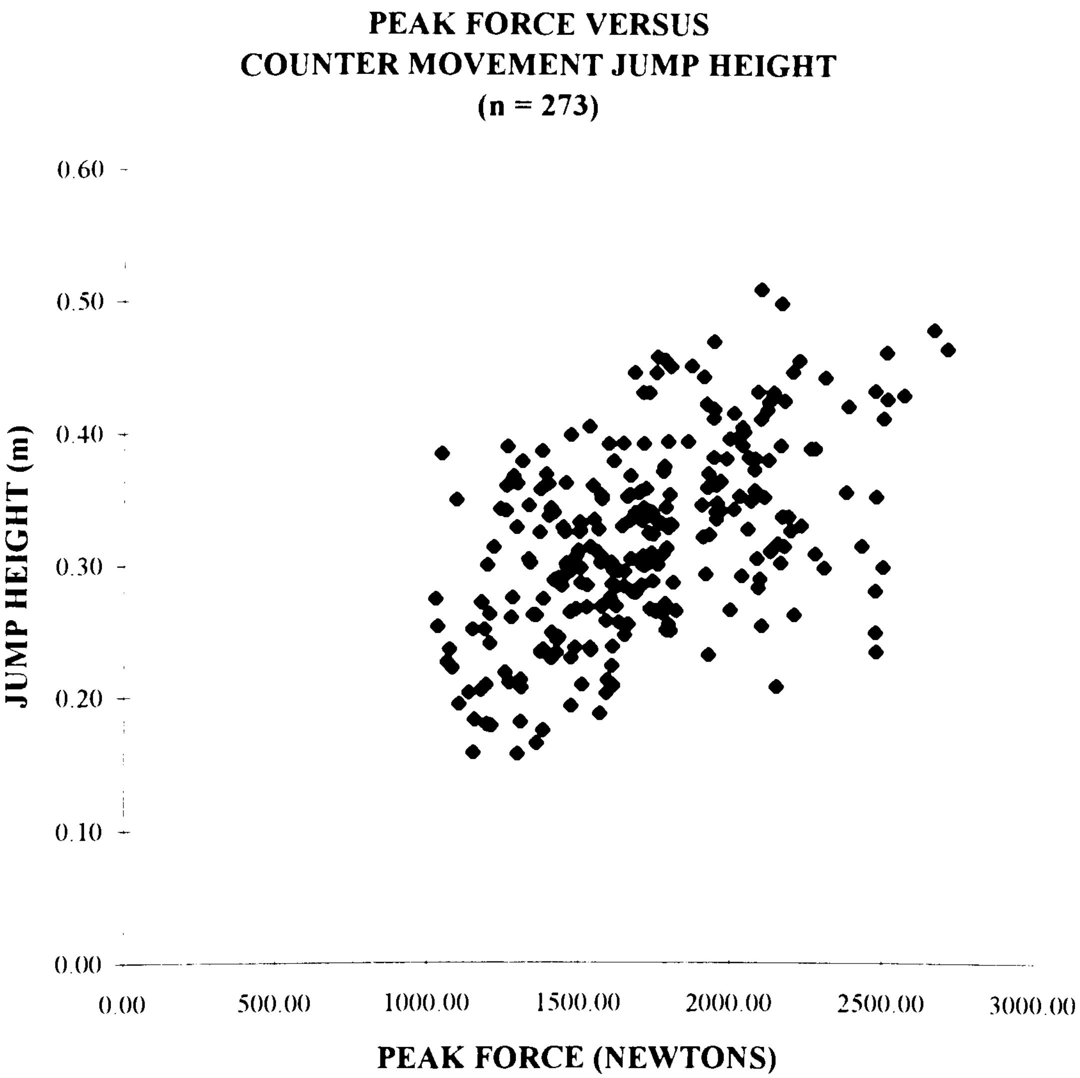

Fig. 4.29: Peak Force Versus Counter Movement Jump Height (r = 0.537, p < 0.001).

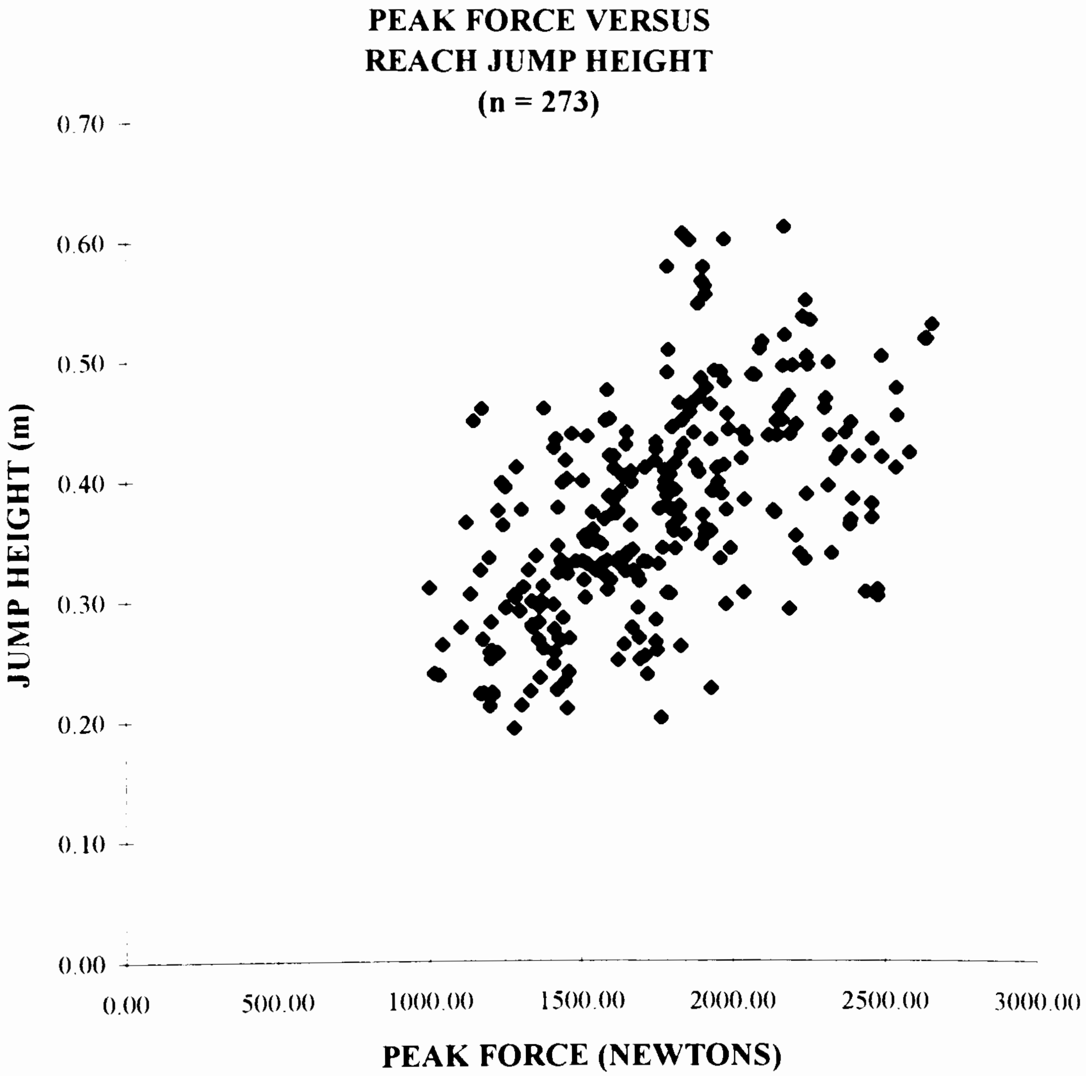

Fig. 4.30: Peak Force Versus Reach Jump Height ($r = 0.543$, $p < 0.001$).

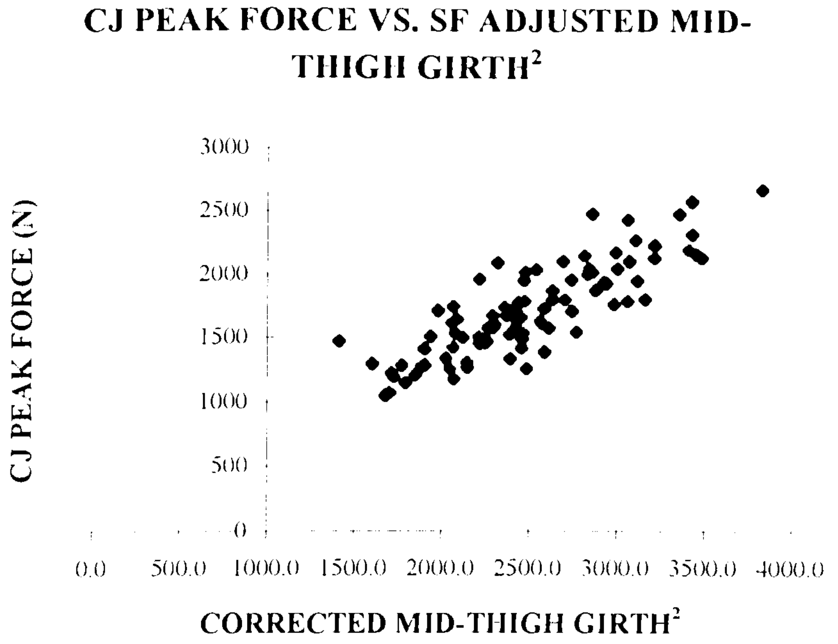

Fig. 4.31: Counter Jump Peak Force (Ordinate) Versus Corrected Mid-Thigh Girth^2; Correlation = 0.842 ($p < 0.001$).

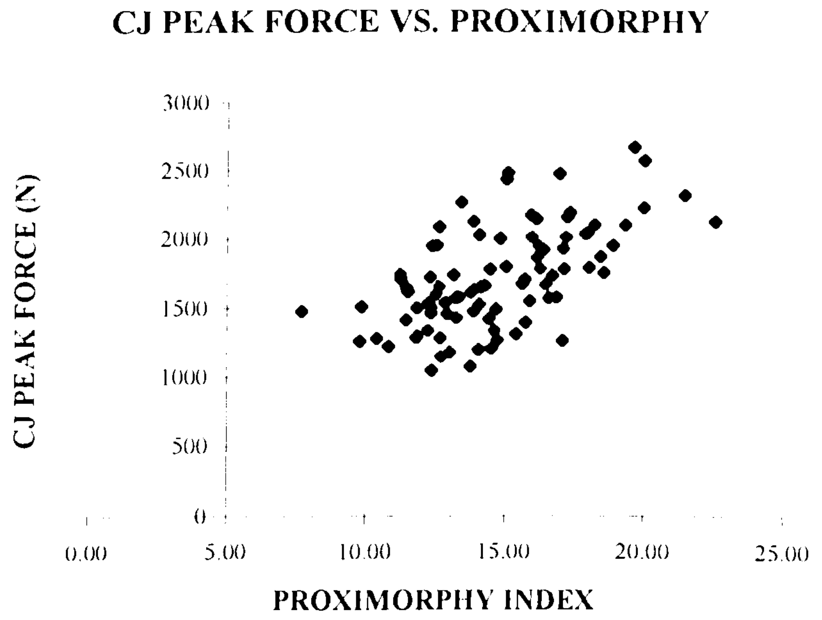

Fig. 4.32: Counter Jump Peak Force (Ordinate) Versus Proximorphy Index; Correlation = 0.596 ($p < 0.001$).

PEAK FORCE (N)	STATIC JUMP n = 197	COUNTER JUMP n = 273	REACH JUMP n = 273
Mean	1659.3	1716.4	1755.5
S.D.	358.6	358.9	375.9
Maximum	2775.5	2721.6	2659.6
Minimum	1060.8	1029.6	1002.4

Table 4.22: Peak Forces in the Three Jump Types.

Table 4.22 shows how the average peak force was highest in the reach jump and lowest in the static jump, and this is in keeping with most of the research cited in Chapter II. The combination of the counter movement and the arm swing normally produces higher peak forces, although the precise mechanism involved is still under debate.

However, a hint of the individual variability encountered was shown by the fact that the maximum peak force recorded was in a static jump, while the minimum peak force occurred in a reach jump (i.e. the extremes show the opposite trend to the averages). Also, the relatively poor correlations of the peak forces with the jump heights support the statement by Dowling and Vamos (1993, p. 95) that a high maximum force may be "necessary but not sufficient" for a good performance.

An interesting finding involved the relatively high (> 0.7) and significant ($p < 0.001$) correlations between the impulse deficits during the counter movements of the CJ and RJ, and the peak forces generated in those jumps (see figure 4.33 below). Do the larger impulse deficits potentiate greater forces by requiring an increased braking of the downward motion, or are the stronger people simply able to increase their acceleration distances greater amounts, thereby incurring greater impulse deficits without deleterious effects on subsequent force generation? It may simply be a correlated effect, with stronger people generally being heavier and incurring a greater impulse deficit with the same counter movement amplitude of a lighter person. This latter hypothesis is supported by high correlations ($r > 0.7$) between mass and the impulse deficits.

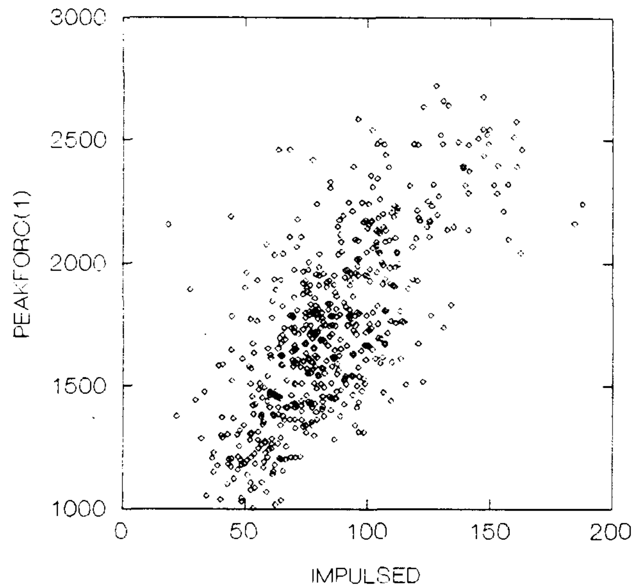

Fig. 4.33: Peak Force (N) Versus Impulse Deficit (Ns) in the Counter Movement and Reach Jumps.

But while bigger impulse deficits were associated with larger peak forces, they were less related to jump height. Figure 4.34, below, shows a group of jumps with approximately 0 deficit. These of course are the static jumps. When they are deleted, $r = 0.278$, $p < 0.001$, for the CJ and RJ with jump height.

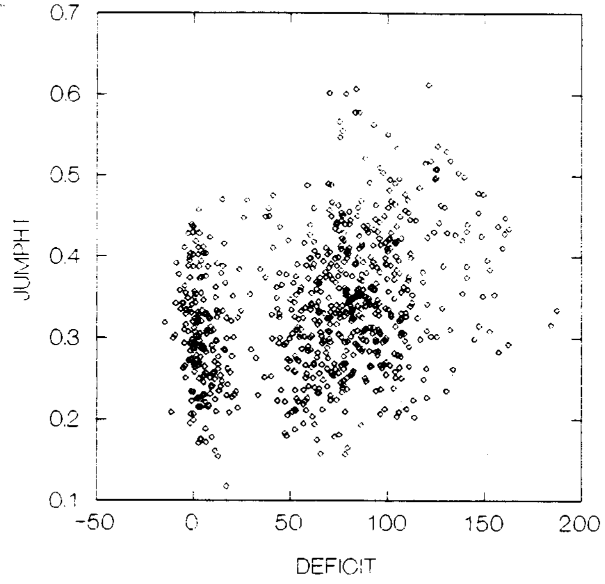

Fig. 4.34: Impulse Deficits (Ns) Versus Jump Heights (m) for All Jump Types.
The group above 0 deficit comprises the static jumps (SJ).
If they are deleted, $r = 0.278$, $p < 0.001$, for the CJ and RJ.

However, Hochmuth (1984) recommends that in jumps which involve a counter movement, the braking thrust (herein termed the 'impulse deficit') should not exceed about one-third of the acceleration thrust (called the 'impulse surplus' in this study). An 'impulse deficit/impulse surplus' ratio was calculated, and was related to the counter movement and reach jump heights, as is shown below (fig. 4.35 and 4.36). Low but significant negative correlations, similar to those found by Dowling and Vamos (1993), were found among the 273 jumps of each type, and are reported with the graphs. While the correlations were similar, the mean values of the ratio appear considerably higher in this study. While there are a number of outliers shown on these charts, no explanatory pattern became evident.

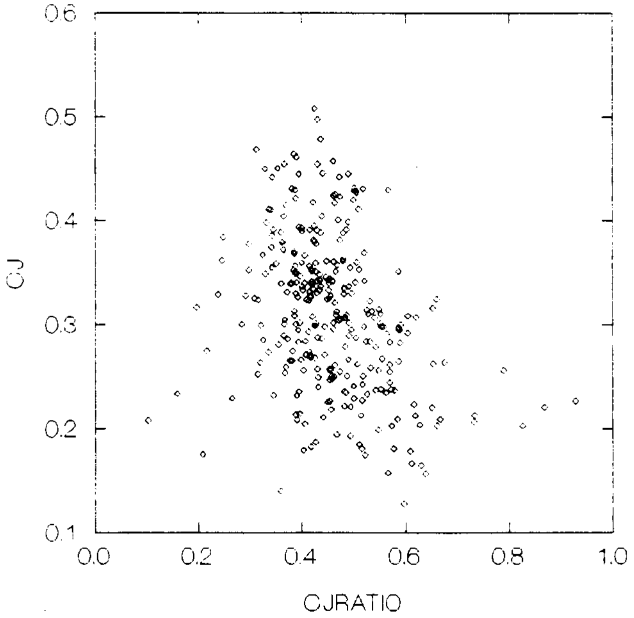

Fig. 4.35: Impulse Deficit/Surplus Ratio Versus Counter Jump Height (m); Correlation = -0.326 (n = 300, p < 0.001).

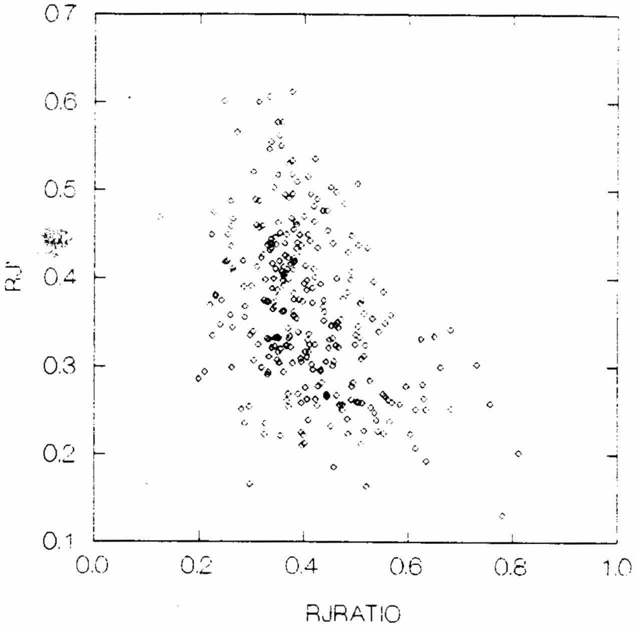

Fig. 4.36: Impulse Deficit/Surplus Ratio Versus Reach Jump Height (m); Correlation = -0.420 (n = 299, $p < 0.001$).

IMPULSE RATIO (DEFICIT/SURPLUS)	COUNTER JUMP n = 300	REACH JUMP n = 299
Mean	0.456	0.406
S.D.	0.105	0.104
Maximum	0.928	0.811
Minimum	0.103	0.124

Table 4.23: Impulse Deficit/Surplus Ratios Versus Counter and Reach Jumps.

The final unweighting phase (i.e. the short duration from maximum upward velocity to take-off) involves forces falling below W, and it results in a slight deceleration and reduction in the velocity at take-off. A low but significant ($p < 0.001$) negative correlation exists between this variable and all three jumps (SJ = -0.464; CJ = - 0.448; RJ = - 0.398). On the one hand, this reduced duration may just be a reflection of a better jumper moving more quickly upwards and leaving the ground sooner after generating the peak force. On the other hand, it may also be indicative of what Hochmuth and Marhold (1977) described as the "principle of late force development". The ability to generate the peak force while the muscle is contracting at a greater velocity is the essence of power.

Chapter V

CONCLUSIONS AND RECOMMENDATIONS

This research investigated the statistical relationships between human macro structure, as measured by anthropometry, and a generic motor performance, the standing vertical jump. One hundred subjects (68 males and 32 females, comprising 59 athletes in various sports and 41 Kinesiology students) underwent forty-two standard somatic measurements. Additional derived variables quantified shape, proportion, and composition. Two new lower extremity shape indices were designed: an *angularity index* for the thigh and shank segments, and a *proximorphy index* (to quantify the extent to which the lower extremity muscle mass was centred near the trunk, as is found among the best animal jumpers).

An anthropometric analogue of an explanatory physics equation provided a theoretical framework for modelling the jumps based on anthropometry. After principal components analyses for data reduction, forced multiple regressions determined the final unisex models, which included $\log_{(\text{base } 10)}$ sum of eight skinfolds and the proximorphy index as the best significant explanatory variables, together accounting for 35% to 50% of the jump height variance. When tested on 68 male professional hockey players, the models actually performed better than on the sample upon which they were based. The proportion of the variability (multiple r) explained by structure was 0.57 - 0.70; a proportion difficult to ignore. Major non-structural causative factors are likely to preclude more precise prediction.

Chapter II ended with a list of seventeen secondary questions which this study attempted to answer, and they have been answered one at a time throughout Chapter IV. But a series of largely independent questions was not the focus of this research. Nor is the ability to predict vertical jumps from structure a worthy end in itself, especially since two of the jumps included here were unnatural, and not found in any sport or physical activity. The prediction of these jumps is trivial if it does not lead to an explanation or a greater understanding of human structure and movement; particularly, how anthropometry may help to define the structure-performance linkage.

More than even this, the research was committed to the process of theoretical modelling - the building of something meaningful from something already known. Since "Newton Rules Biology", there can be no argument with the equation that was used as the basis for the anthropometric analogue.

$$h = F \times \frac{1}{m} \times d \times \frac{1}{g} \qquad \text{(Eq. 44)}$$

While the modelling process was correlational and therefore could involve no definitive experimental proof of causation, the framework for the anthropometric analogue is theoretically sound. The choosing of the anthropometric variables to represent the physics of jumping required both empirical evidence and a theoretical perspective. However, while common sense may not *rule* biology, it has a large role to play in understanding it.

Two models were chosen for each jump type, according to reasonably established criteria. These models really represent a "family" of potential models, many of which may be nearly as good as the ones chosen (and for some samples, perhaps better!). In other words, it is likely that the variables themselves will be useful for most samples, but the coefficients may change considerably. With some subject samples who have reduced variance in the model variables, other appropriate candidate variables with greater inter-subject variance may have to be substituted.

It was observed that structure could better predict the peak forces in the jumps than it could predict the jump heights. This suggests that even a skill as "simple" as a vertical jump is complex enough to involve skill and perhaps other non-macro structural elements, and to require kinetic, kinematic and electromyographic description for a fuller understanding of its execution. Nonetheless, the predictive power of the models developed herein was substantial. It is clear that structure must be taken into account when performing even the most basic of skills.

The highest correlation among all three types of jumps was between the counter movement jump and the reach jump, even though the biggest absolute difference in jump heights occurred between these two types. This suggests that while the addition of the arms may add more to the height of a jump than the addition of a counter movement, the counter movement may act as a unifying factor in reducing the between-jump-type variance among any jumps that include it.

As expected, skinfold-corrected mid-thigh girths^2 and the $\log_{(10)}$ mass-adjusted sum of skinfolds were about the best individual correlates (positive and negative, respectively) of the vertical jump heights. However, it also seems that a proximorphic shape (as operationally defined in chapter III) is of considerable benefit in jumping! As described above, it may have direct biomechanical benefits (e.g. from a reduced moment of inertia around proximal joints), or it may be correlated with increased strength, since people who weight train become stronger and their thigh muscles may hypertrophy more than their calf muscles. Further work should be done to investigate the possible roles that this aspect of shape may have in producing performance.

Recommendations:

1. This type of study should be extended to a more sedentary population including some more ponderous people with greater adiposity, since they were not well represented in this study.

2. Whenever possible, more time should be given to subjects to learn how to perform static jumps without *any* counter movement 'unweighting'. While many subjects had no difficulty with this technique, many others did unweight down to the cut-off point of 80% of body weight, and there were 3 subjects who could not make that criterion even once in the three attempts.

3. A longitudinal study should be undertaken to examine how the proximorphic index and the skinfold-corrected girths change as a result of strength training, and how those changes may correlate with performance differences.

4. Multi-dimensional studies of performance need to be undertaken, in which anthropometric assessment would be linked with kinetic, kinematic and electromyographic analyses. The linkage of precise measures of structure to EMG data, segment angular accelerations and net ground reaction force-time and power-time curves, is likely to lead to a much greater understanding of how performances are accomplished.

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APPENDICES

APPENDIX A

(Regression of Jumps From Other Jump Types: Reformatted from Systat for Windows. Version 5.0)

```
------------------------------------------------------------------------------------------------
>MODEL SJHT = CONSTANT+CJHT
>ESTIMATE

DEP VAR:                                             SJHT
N:                                                   88
MULTIPLE R:                                          0.879
SQUARED MULTIPLE R:                                  0.773
ADJUSTED SQUARED MULTIPLE R:                         0.770
STANDARD ERROR OF ESTIMATE:                          0.033

VARIABLE      COEFFICIENT  STD ERROR    STD COEF      TOL.    T        P(2 TAIL)

CONSTANT      0.018        0.018        0.000          .        1.004  0.318
CJHT          0.869        0.051        0.879         1.000   17.107  0.000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES      DF  MEAN-SQUARE     F-RATIO          P

REGRESSION    0.314                1    0.314         292.658          0.000
RESIDUAL      0.092               86    0.001

------------------------------------------------------------------------------------------------
>MODEL SJHT = CONSTANT+RJHT
>ESTIMATE

DEP VAR:                                             SJHT
N:                                                   88
MULTIPLE R:                                          0.840
SQUARED MULTIPLE R:                                  0.706
ADJUSTED SQUARED MULTIPLE R:                         0.703
STANDARD ERROR OF ESTIMATE:                          0.037

VARIABLE      COEFFICIENT  STD ERROR    STD COEF      TOL.    T        P(2 TAIL)

CONSTANT      0.058        0.018        0.000          .        3.204  0.002
RJHT          0.644        0.045        0.840         1.000   14.374  0.000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES      DF    MEAN-SQUARE         F-RATIO        P

REGRESSION    0.287                1     0.287              206.601        0.000
RESIDUAL      0.119               86     0.001

------------------------------------------------------------------------------------------------
```

```
------------------------------------------------------------------------------------------------------
>MODEL CJHT = CONSTANT+SJHT
>ESTIMATE

DEP VAR:                                             CJHT
N:                                                   88
MULTIPLE R:                                          0.879
SQUARED MULTIPLE R:                                  0.773
ADJUSTED SQUARED MULTIPLE R:                         0.770
STANDARD ERROR OF ESTIMATE:                          0.033

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.    T        P(2 TAIL)

CONSTANT     0.061        0.017        0.000          .      3.690  0.000
SJHT         0.890        0.052        0.879        1.000   17.107  0.000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES     DF    MEAN-SQUARE        F-RATIO        P

REGRESSION   0.322               1    0.322              292.658        0.000
RESIDUAL     0.095              86    0.001

------------------------------------------------------------------------------------------------------
>MODEL CJHT = CONSTANT+RJHT
>ESTIMATE

DEP VAR:                                             CJHT
N:                                                   91
MULTIPLE R:                                          0.934
SQUARED MULTIPLE R:                                  0.872
ADJUSTED SQUARED MULTIPLE R:                         0.870
STANDARD ERROR OF ESTIMATE:                          0.025

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.    T        P(2 TAIL)

CONSTANT     0.055        0.012        0.000          .      4.581  0.000
RJHT         0.722        0.029        0.934        1.000   24.576  0.000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES     DF    MEAN-SQUARE        F-RATIO        P

REGRESSION   0.371               1    0.371              603.966        0.000
RESIDUAL     0.055              89    0.001

------------------------------------------------------------------------------------------------------
```

```
----------------------------------------------------------------------------------------------------------
>MODEL RJHT = CONSTANT+SJHT
>ESTIMATE

DEP VAR:                                          RJHT
N:                                                88
MULTIPLE R:                                       0.840
SQUARED MULTIPLE R:                               0.706
ADJUSTED SQUARED MULTIPLE R:                      0.703
STANDARD ERROR OF ESTIMATE:                       0.049

VARIABLE      COEFFICIENT  STD ERROR     STD COEF      TOL.    T        P(2 TAIL)

CONSTANT      0.052        0.024         0.000           .      2.147   0.035
SJHT          1.096        0.076         0.840         1.000   14.374   0.000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES    DF       MEAN-SQUARE           F-RATIO         P

REGRESSION    0.488              1       0.488                 206.601         0.000
RESIDUAL      0.203             86       0.002

----------------------------------------------------------------------------------------------------------
>MODEL RJHT = CONSTANT+CJHT
>ESTIMATE

DEP VAR:                                          RJHT
N:                                                91
MULTIPLE R:                                       0.934
SQUARED MULTIPLE R:                               0.872
ADJUSTED SQUARED MULTIPLE R:                      0.870
STANDARD ERROR OF ESTIMATE:                       0.032

VARIABLE      COEFFICIENT  STD ERROR     STD COEF      TOL.    T        P(2 TAIL)

CONSTANT      -0.015       0.017         0.000           .     -0.883   0.379
CJHT           1.207       0.049         0.934         1.000   24.576   0.000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES    DF       MEAN-SQUARE           F-RATIO         P

REGRESSION    0.620              1       0.620                 603.966         0.000
RESIDUAL      0.091             89       0.001

----------------------------------------------------------------------------------------------------------
```

APPENDIX B

(Principal Components Analysis on Anthropometry: Reformatted from Systat for Windows. Version 5.0)

```
>NUMBER=4
>TYPE=CORRELATION
>FACTOR MASS WEIGHT STATURE SITHT SPAN UPARML FORARML HANDL SPINHT
>TROCHHT THIGHL TIBLTHT LEGL FOOTL TRICSF SUBSCSF BICEPSF ILIACSF SUPSPSF
>ABDOMSF FRTHSF MEDCFSF SOS APCHEST TRCHBR BIACRBR BIILBR HUMERBR WRISTBR
>HANDBR FEMURBR HEADGTH NECKGTH ARMRELG ARMRG2 ARMFLG ARMFLG2 FORAMG
>FORMG2 FORMG2M WRISTG WRISTG2 CHESTG CHESTG2 WAISTG WAISTG2 GLUTG
>GLUTG2 THIGHG THIGHG2 MIDTHG CORMTHG CMTHG2 CMTH2M CFG CORCFG CORCFG2
>ANKLEG ANKLG2 STATURZ SITHTZ SPANZ UPARMLZ FORAMLZ HANDLZ THIGHLZ
>TIBLHTZ FOOTLZ TRICEPZ SUBSCPZ BICEPSZ ILIACZ SUPRSPZ ABDOMZ FRTHZ
>MCALFZ APCHSTZ TRCHSTZ BIACRZ BIILBRZ HUMBRZ FEMBRZ HEADZ NECKZ ARMRLGZ
>ARMFLGZ FORAMGZ WRISTGZ CHESTGZ WAISTGZ GLUTGZ THIGHGZ CALFGZ ANKLGZ
>ANGULTH ANGULSH PROXIMOR CRURALI ENDOMORP MESOMORP ECTOMORP SKINC
>ADIPOSE MUSCLE MUSC MUSC23 BONE RESIDUAL SOSW LOGSOSW LSOSW3
```

```
LATENT ROOTS (EIGENVALUES)

     1        2        3        4        5        6        7        8        9        10
     45.321   25.355   10.584   5.088    3.814    2.460    2.179    1.768    1.619    1.315

     11       12       13       14       15       16       17       18       19       20
     1.186    0.982    0.942    0.877    0.818    0.674    0.617    0.584    0.535    0.439

     21       22       23       24       25       26       27       28       29       30
     0.403    0.374    0.367    0.338    0.289    0.247    0.239    0.210    0.186    0.159

     31       32       33       34       35       36       37       38       39       40
     0.156    0.126    0.112    0.094    0.088    0.072    0.069    0.053    0.051    0.046

     41       42       43       44       45       46       47       48       49       50
     0.038    0.029    0.024    0.018    0.015    0.010    0.006    0.005    0.004    0.003

     51       52       53       54       55       56       57       58       59       60
     0.003    0.002    0.001    0.001    0.001    0.001    0.001    0.001    0.001    0.000

     61       62       63       64       65       66       67       68       69       70
     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000

     71       72       73       74       75       76       77       78       79       80
     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000

     81       82       83       84       85       86       87       88       89       90
     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000

     91       92       93       94       95       96       97       98       99       100
     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    -0.000

     101      102      103      104      105      106      107      108      109      110
```

-0.000 -0.000 -0.000 -0.000 -0.000 -0.000 -0.000 -0.000 -0.000 -0.000

111
-0.000

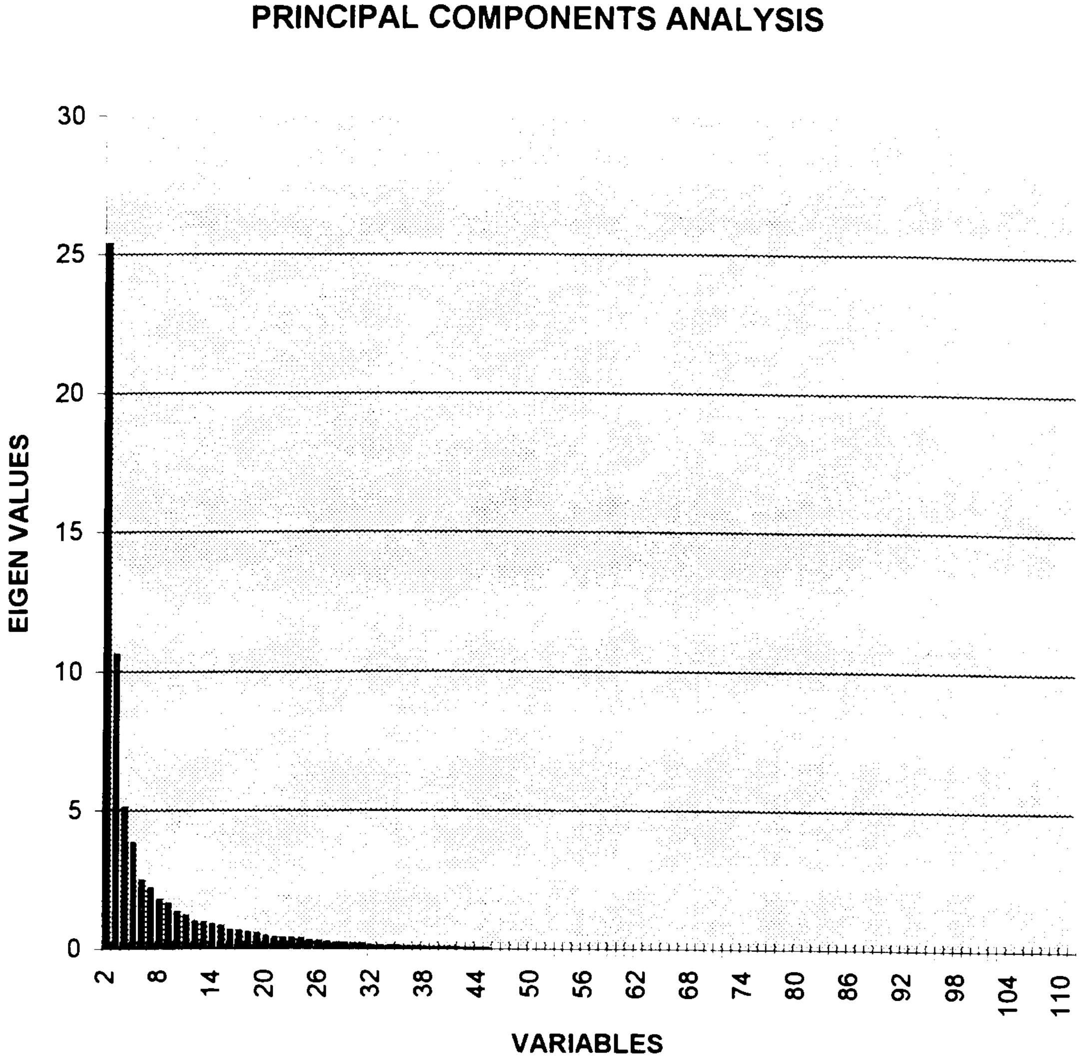

Fig. A.1: Principal Components Analysis: Eigenvalues Versus Anthropometric Variables.

COMPONENT LOADINGS

	1	2	3	4
MASS	0.959	-0.209	0.146	-0.068
WEIGHT	0.959	-0.209	0.146	-0.068
STATURE	0.807	0.136	0.518	-0.012
SITHT	0.812	0.143	0.278	-0.080
SPAN	0.831	0.229	0.432	0.119
UPARML	0.763	0.147	0.487	0.077
FORARML	0.814	0.205	0.374	0.130
HANDL	0.825	0.217	0.242	0.083
SPINHT	0.743	0.121	0.589	-0.023
TROCHHT	0.737	0.095	0.628	0.053
THIGHL	0.640	0.069	0.678	0.067
TIBLTHT	0.769	0.080	0.560	0.033
LEGL	0.717	0.005	0.599	0.010
FOOTL	0.857	0.140	0.287	0.047
TRICSF	-0.184	-0.905	0.096	0.132
SUBSCSF	0.188	-0.812	-0.058	0.365
BICEPSF	-0.096	-0.894	0.091	0.146
ILIACSF	0.284	-0.808	0.001	0.323
SUPSPSF	0.199	-0.850	0.048	0.308
ABDOMSF	0.122	-0.871	-0.019	0.276
FRTHSF	-0.291	-0.843	0.241	-0.042
MEDCFSF	-0.177	-0.877	0.174	-0.054
SOS	0.019	-0.962	0.080	0.209
APCHEST	0.820	-0.083	-0.001	0.125
TRCHBR	0.893	-0.024	0.037	0.115
BIACRBR	0.804	0.229	0.107	0.157
BIILBR	0.535	-0.290	0.438	-0.060
HUMERBR	0.879	0.157	-0.012	0.166
WRISTBR	0.859	0.306	0.022	0.004
HANDBR	0.830	0.253	-0.050	0.123
FEMURBR	0.876	-0.018	0.117	-0.009
HEADGTH	0.685	0.066	0.040	0.083
NECKGTH	0.897	0.071	-0.200	0.205
ARMRELG	0.888	-0.249	-0.240	0.027
ARMRG2	0.883	-0.267	-0.233	0.021
ARMFLXG	0.923	-0.088	-0.223	0.049
ARMFLG2	0.919	-0.108	-0.216	0.034
FORARMG	0.957	0.024	-0.154	0.045
FORMG2	0.957	0.001	-0.151	0.030
FORMG2M	-0.026	0.446	-0.647	0.256
WRISTG	0.909	0.155	-0.001	0.009
WRISTG2	0.909	0.136	0.003	-0.002
CHESTG	0.934	-0.094	-0.066	0.121
CHESTG2	0.929	-0.118	-0.059	0.112
WAISTG	0.920	-0.206	-0.105	0.139
WAISTG2	0.909	-0.243	-0.098	0.136
GLUTG	0.764	-0.490	0.286	-0.171
GLUTG2	0.763	-0.498	0.281	-0.156

THIGHG	0.725	-0.573	0.095	-0.269
THIGHG2	0.730	-0.577	0.094	-0.256
MIDTHG	0.832	-0.369	-0.015	-0.272
CORMTHG	0.905	0.133	-0.146	-0.220
CMTHG2	0.904	0.113	-0.147	-0.234
CMTHG2M	-0.004	0.524	-0.509	-0.247
CALFG	0.751	-0.334	0.098	-0.422
CORCFG	0.820	0.163	-0.002	-0.376
CORCFG2	0.815	0.141	-0.005	-0.383
ANKLEG	0.802	-0.136	0.220	-0.311
ANKLG2	0.801	-0.157	0.216	-0.302
STATURZ	-0.528	0.539	0.537	0.106
SITHTZ	-0.620	0.497	0.103	0.012
SPANZ	-0.209	0.691	0.476	0.313
UPARMLZ	-0.180	0.491	0.559	0.227
FORAMLZ	-0.013	0.589	0.395	0.309
HANDLZ	-0.090	0.598	0.156	0.228
THIGHLZ	-0.295	0.310	0.742	0.171
TIBLHTZ	-0.203	0.401	0.683	0.156
FOOTLZ	0.067	0.546	0.274	0.188
TRICEPZ	-0.332	-0.878	0.069	0.106
SUBSCPZ	0.040	-0.807	-0.089	0.375
BICEPSZ	-0.233	-0.871	0.066	0.130
ILIACZ	0.166	-0.822	-0.025	0.334
SUPRSPZ	0.076	-0.875	0.027	0.316
ABDOMZ	-0.009	-0.873	-0.042	0.275
FRTHZ	-0.417	-0.795	0.208	-0.057
MCALFZ	-0.322	-0.840	0.146	-0.075
APCHSTZ	0.400	0.060	-0.149	0.258
TRCHSTZ	0.342	0.245	-0.152	0.312
BIACRZ	-0.104	0.576	-0.045	0.322
BIILBRZ	-0.472	-0.134	0.356	-0.017
HUMBRZ	0.130	0.530	-0.233	0.374
FEMBRZ	-0.011	0.305	-0.048	0.103
HEADZ	-0.805	0.265	-0.170	0.136
NECKZ	0.443	0.318	-0.493	0.425
ARMRLGZ	0.578	-0.235	-0.578	0.118
ARMFLGZ	0.676	0.034	-0.525	0.156
FORAMGZ	0.602	0.307	-0.508	0.191
WRISTGZ	0.258	0.552	-0.228	0.121
CHESTGZ	0.482	0.113	-0.397	0.374
WAISTGZ	0.656	-0.150	-0.382	0.343
GLUTGZ	-0.416	-0.639	0.279	-0.246
THIGHGZ	-0.136	-0.765	-0.052	-0.403
CALFGZ	-0.203	-0.283	-0.064	-0.634
ANKLGZ	-0.125	0.061	0.142	-0.464
ANGULTH	0.203	-0.539	-0.434	-0.322
ANGULSH	-0.025	-0.187	-0.461	-0.427
PROXIMOR	0.564	0.040	-0.408	-0.003
CRURALI	0.177	0.020	-0.255	-0.066
ENDOMORP	-0.082	-0.941	-0.040	0.233
MESOMORP	0.671	-0.125	-0.619	-0.057

```
ECTOMORP   -0.521   0.520   0.545   0.120
SKINC       0.948  -0.093   0.277  -0.054
ADIPOSE     0.298  -0.865   0.285   0.181
MUSCLE      0.973   0.071  -0.131  -0.091
MUSC        0.301   0.592  -0.619  -0.013
MUSC23      0.972   0.089  -0.131  -0.081
BONE        0.913   0.037   0.173   0.085
RESIDUAL    0.967   0.033   0.012   0.032
SOSW       -0.440  -0.862  -0.001   0.157
LOGSOSW    -0.470  -0.828   0.002   0.133
LSOSW3     -0.456  -0.857   0.001   0.142

  VARIANCE EXPLAINED BY COMPONENTS

             1        2        3       4
          45.321   25.355   10.584   5.088

PERCENT OF TOTAL VARIANCE EXPLAINED

             1        2        3       4
          40.829   22.842   9.535    4.584
```

APPENDIX C

(Multiple Regression Model Development (***Static Jump***): Reformatted from Systat for Windows V. 5.0)

```
----------------------------------------------------------------------------------------------------
>MODEL SJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2
>ESTIMATE

DEP VAR:                                              SJHT
N:                                                    88
MULTIPLE R:                                           0.533
SQUARED MULTIPLE R:                                   0.284
ADJUSTED SQUARED MULTIPLE R:                          0.276
STANDARD ERROR OF ESTIMATE:                           0.058169

VARIABLE      COEFFICIENT   STD ERROR     STD COEF      TOL.    T        P(2 TAIL)

CONSTANT      0.129487      0.031992      0.000000        .     4.048    0.00011
CMTHG2        0.000073      0.000013      0.532853      1.000   5.840    0.00000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES     DF     MEAN-SQUARE              F-RATIO        P

REGRESSION    0.115385            1     0.115385                 34.100317      0.0000
RESIDUAL      0.290997           86     0.003384

----------------------------------------------------------------------------------------------------
>MODEL SJHT = CONSTANT+PROXIMORPHY
>ESTIMATE

DEP VAR:                                              SJHT
N:                                                    88
MULTIPLE R:                                           0.503
SQUARED MULTIPLE R:                                   0.253
ADJUSTED SQUARED MULTIPLE R:                          0.244
STANDARD ERROR OF ESTIMATE:                           0.059421

VARIABLE      COEFFICIENT   STD ERROR     STD COEF      TOL.    T        P(2 TAIL)

CONSTANT      0.117203      0.036804      0.000000        .     3.185    0.00202
PROXIMOR      0.013267      0.002460      0.502791      1.000   5.394    0.00000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES     DF     MEAN-SQUARE              F-RATIO        P

REGRESSION    0.102733            1     0.102733                 29.096218      0.0000
RESIDUAL      0.303649           86     0.003531

----------------------------------------------------------------------------------------------------
```

```
------------------------------------------------------------------------------------------------------------
>MODEL SJHT = CONSTANT+LOGSOSW
>ESTIMATE

DEP VAR:                                          SJHT
N:                                                88
MULTIPLE R:                                       0.559
SQUARED MULTIPLE R:                               0.312
ADJUSTED SQUARED MULTIPLE R:                      0.304
STANDARD ERROR OF ESTIMATE:                       0.057020

VARIABLE      COEFFICIENT   STD ERROR     STD COEF      TOL.     T        P(2 TAIL)

CONSTANT       0.612826     0.048438       0.000000       .      12.652   0.00000
LOGSOSW       -0.215323     0.034484      -0.558520     1.000    -6.244   0.00000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES     DF     MEAN-SQUARE          F-RATIO          P

REGRESSION    0.126769            1     0.126769             38.989984        0.0000
RESIDUAL      0.279613           86     0.003251

------------------------------------------------------------------------------------------------------------
>MODEL SJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)²+PROXIMORPHY+LOGSOSW
>ESTIMATE

DEP VAR:                                          SJHT
N:                                                88
MULTIPLE R:                                       0.650
SQUARED MULTIPLE R:                               0.422
ADJUSTED SQUARED MULTIPLE R:                      0.402
STANDARD ERROR OF ESTIMATE:                       0.052874

VARIABLE      COEFFICIENT   STD ERROR     STD COEF      TOL.     T        P(2 TAIL)

CONSTANT       0.394807     0.079700       0.000000       .       4.954   0.00000
CMTHG2         0.000008     0.000020       0.055346     0.321     0.378   0.70631
PROXIMOR       0.008365     0.003380       0.317002     0.419     2.475   0.01534
LOGSOSW       -0.161012     0.039432      -0.417643     0.658    -4.083   0.00010

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES     DF     MEAN-SQUARE          F-RATIO          P

REGRESSION    0.171550            3     0.057183             20.454575        0.0000
RESIDUAL      0.234832           84     0.002796

------------------------------------------------------------------------------------------------------------
```

STATIC JUMP MODEL

```
>MODEL SJHT = CONSTANT+PROXIMORPHY+LOGSOSW
>ESTIMATE

DEP VAR:                                        SJHT
N:                                              88
MULTIPLE R:                                     0.649
SQUARED MULTIPLE R:                             0.421
ADJUSTED SQUARED MULTIPLE R:                    0.408
STANDARD ERROR OF ESTIMATE:                     0.052606

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.    T       P(2 TAIL)

CONSTANT      0.410671    0.067419      0.000000      .      6.091  0.00000
PROXIMOR      0.009290    0.002320      0.352063    0.881    4.005  0.00013
LOGSOSW      -0.168521    0.033893     -0.437122    0.881   -4.972  0.00000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES     DF     MEAN-SQUARE         F-RATIO       P

REGRESSION   0.171150            2     0.085575            30.922164     0.0000
RESIDUAL     0.235232           85     0.002767
```

STATIC JUMP MODEL BACKUP

```
>MODEL SJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2+LOGSOSW
>ESTIMATE

DEP VAR:                                        SJHT
N:                                              88
MULTIPLE R:                                     0.616
SQUARED MULTIPLE R:                             0.380
ADJUSTED SQUARED MULTIPLE R:                    0.365
STANDARD ERROR OF ESTIMATE:                     0.054444

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.    T       P(2 TAIL)

CONSTANT      0.406254    0.081929      0.000000      .      4.959  0.00000
CMTHG2        0.000044    0.000014      0.317613    0.675    3.055  0.00301
LOGSOSW      -0.145481    0.040086     -0.377359    0.675   -3.629  0.00048

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES     DF     MEAN-SQUARE         F-RATIO       P

REGRESSION   0.154427            2     0.077213            26.048752     0.0000
RESIDUAL     0.251956           85     0.002964
```

APPENDIX D

(Multiple Regression Model Development (***Counter Jump***): Reformatted from Systat for Windows V. 5.0)

```
-----------------------------------------------------------------------------------------------
>MODEL CJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2
>ESTIMATE

DEP VAR:                                        CJHT
N:                                              91
MULTIPLE R:                                     0.590
SQUARED MULTIPLE R:                             0.348
ADJUSTED SQUARED MULTIPLE R:                    0.341
STANDARD ERROR OF ESTIMATE:                     0.055868

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.    T       P(2 TAIL)

CONSTANT     0.137016     0.030008     0.000000       .     4.566   0.00002
CMTHG2       0.000081     0.000012     0.589920     1.000   6.892   0.00000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES    DF    MEAN-SQUARE        F-RATIO       P

REGRESSION   0.148272           1    0.148272           47.504193     0.0000
RESIDUAL     0.277791          89    0.003121

-----------------------------------------------------------------------------------------------
>MODEL CJHT = CONSTANT+PROXIMORPHY
>ESTIMATE

DEP VAR:                                        CJHT
N:                                              91
MULTIPLE R:                                     0.555
SQUARED MULTIPLE R:                             0.308
ADJUSTED SQUARED MULTIPLE R:                    0.301
STANDARD ERROR OF ESTIMATE:                     0.057541

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.    T       P(2 TAIL)

CONSTANT     0.134984     0.033079     0.000000       .     4.081   0.00010
PROXIMOR     0.013903     0.002207     0.555309     1.000   6.299   0.00000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES    DF    MEAN-SQUARE        F-RATIO       P

REGRESSION   0.131384           1    0.131384           39.681098     0.0000
RESIDUAL     0.294679          89    0.003311

-----------------------------------------------------------------------------------------------
```

```
------------------------------------------------------------------------------------------------
>MODEL CJHT = CONSTANT+LOGSOSW
>ESTIMATE

DEP VAR:                                          CJHT
N:                                                91
MULTIPLE R:                                       0.581
SQUARED MULTIPLE R:                               0.338
ADJUSTED SQUARED MULTIPLE R:                      0.330
STANDARD ERROR OF ESTIMATE:                       0.056307

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.     T        P(2 TAIL)

CONSTANT      0.656369     0.047351     0.000000     .       13.862   0.00000
LOGSOSW      -0.226406     0.033608    -0.581132    1.000    -6.737   0.00000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES    DF    MEAN-SQUARE        F-RATIO         P

REGRESSION   0.143888           1    0.143888           45.383050       0.0000
RESIDUAL     0.282176          89    0.003171

------------------------------------------------------------------------------------------------
>MODEL CJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2+PROXIMORPHY+LOGSOSW
>ESTIMATE

DEP VAR:                                          CJHT
N:                                                91
MULTIPLE R:                                       0.701
SQUARED MULTIPLE R:                               0.491
ADJUSTED SQUARED MULTIPLE R:                      0.474
STANDARD ERROR OF ESTIMATE:                       0.049924

VARIABLE     COEFFICIENT  STD ERROR    STD COEF     TOL.     T        P(2 TAIL)

CONSTANT      0.407618     0.072986     0.000000     .        5.585   0.00000
CMTHG2        0.000012     0.000019     0.085566    0.310     0.623   0.53485
PROXIMOR      0.008888     0.003014     0.355016    0.404     2.949   0.00409
LOGSOSW      -0.163209     0.036585    -0.418920    0.663    -4.461   0.00002

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES    DF    MEAN-SQUARE        F-RATIO         P

REGRESSION   0.209226           3    0.069742           27.982101       0.0000
RESIDUAL     0.216837          87    0.002492

------------------------------------------------------------------------------------------------
```

COUNTER JUMP MODEL

>MODEL CJHT = CONSTANT+PROXIMORPHY+LOGSOS$_W$
>ESTIMATE

```
DEP VAR:                                         CJHT
N:                                               91
MULTIPLE R:                                      0.699
SQUARED MULTIPLE R:                              0.489
ADJUSTED SQUARED MULTIPLE R:                     0.477
STANDARD ERROR OF ESTIMATE:                      0.049750

VARIABLE     COEFFICIENT   STD ERROR    STD COEF      TOL.     T       P(2 TAIL)

CONSTANT      0.432762     0.060604     0.000000       .       7.141   0.00000
PROXIMOR      0.010280     0.002016     0.410624     0.896     5.100   0.00000
LOGSOSW      -0.174825     0.031369    -0.448735     0.896    -5.573   0.00000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES    DF    MEAN-SQUARE        F-RATIO       P

REGRESSION   0.208259           2    0.104129           42.071486     0.0000
RESIDUAL     0.217805          88    0.002475
```

COUNTER JUMP MODEL BACKUP

>MODEL CJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2+LOGSOS$_W$
>ESTIMATE

```
DEP VAR:                                         CJHT
N:                                               91
MULTIPLE R:                                      0.663
SQUARED MULTIPLE R:                              0.440
ADJUSTED SQUARED MULTIPLE R:                     0.427
STANDARD ERROR OF ESTIMATE:                      0.052061

VARIABLE     COEFFICIENT   STD ERROR    STD COEF      TOL.     T       P(2 TAIL)

CONSTANT      0.406488     0.076110     0.000000       .       5.341   0.00000
CMTHG2        0.000053     0.000013     0.385764     0.689     4.014   0.00013
LOGSOSW      -0.142546     0.037445    -0.365882     0.689    -3.807   0.00026

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES    DF    MEAN-SQUARE        F-RATIO       P

REGRESSION   0.187551           2    0.093776           34.598850     0.0000
RESIDUAL     0.238512          88    0.002710
```

APPENDIX E

(Multiple Regression Model Development (***Reach Jump***): Reformatted from Systat for Windows V. 5.0)

```
-------------------------------------------------------------------------------------------------------------------
>MODEL RJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2
>ESTIMATE

DEP VAR:                                              RJHT
N:                                                    91
MULTIPLE R:                                           0.502
SQUARED MULTIPLE R:                                   0.252
ADJUSTED SQUARED MULTIPLE R:                          0.244
STANDARD ERROR OF ESTIMATE:                           0.077334

VARIABLE     COEFFICIENT  STD ERROR    STD COEF       TOL.     T        P(2 TAIL)

CONSTANT     0.171891     0.041538     0.000000        .       4.138    0.00008
CMTHG2       0.000089     0.000016     0.502128       1.000    5.478    0.00000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES      DF    MEAN-SQUARE              F-RATIO         P

REGRESSION   0.179448             1    0.179448                 30.004975       0.0000
RESIDUAL     0.532275            89    0.005981

-------------------------------------------------------------------------------------------------------------------
>MODEL RJHT = CONSTANT+PROXIMORPHY
>ESTIMATE

DEP VAR:                                              RJHT
N:                                                    91
MULTIPLE R:                                           0.494
SQUARED MULTIPLE R:                                   0.244
ADJUSTED SQUARED MULTIPLE R:                          0.236
STANDARD ERROR OF ESTIMATE:                           0.077745

VARIABLE     COEFFICIENT  STD ERROR    STD COEF       TOL.     T        P(2 TAIL)

CONSTANT     0.159422     0.044694     0.000000        .       3.567    0.00058
PROXIMOR     0.015989     0.002982     0.494130       1.000    5.362    0.00000

ANALYSIS OF VARIANCE

SOURCE       SUM-OF-SQUARES      DF    MEAN-SQUARE              F-RATIO         P

REGRESSION   0.173778             1    0.173778                 28.750536       0.0000
RESIDUAL     0.537945            89    0.006044

-------------------------------------------------------------------------------------------------------------------
```

```
-----------------------------------------------------------------------------------------------------------
>MODEL RJHT = CONSTANT+LOGSOSW
>ESTIMATE

DEP VAR:                                      RJHT
N:                                            91
MULTIPLE R:                                   0.506
SQUARED MULTIPLE R:                           0.257
ADJUSTED SQUARED MULTIPLE R:                  0.248
STANDARD ERROR OF ESTIMATE:                   0.077108

VARIABLE      COEFFICIENT  STD ERROR    STD COEF      TOL.     T        P(2 TAIL)

CONSTANT       0.751559     0.064844     0.000000       .      11.590   0.00000
LOGSOSW       -0.255023     0.046023    -0.506464     1.000    -5.541   0.00000

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES     DF    MEAN-SQUARE          F-RATIO        P

REGRESSION    0.182561            1    0.182561             30.704969      0.0000
RESIDUAL      0.529162           89    0.005946

-----------------------------------------------------------------------------------------------------------
>MODEL RJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2+PROXIMORPHY+LOGSOSW
>ESTIMATE

DEP VAR:                                      RJHT
N:                                            91
MULTIPLE R:                                   0.615
SQUARED MULTIPLE R:                           0.379
ADJUSTED SQUARED MULTIPLE R:                  0.357
STANDARD ERROR OF ESTIMATE:                   0.071292

VARIABLE      COEFFICIENT  STD ERROR    STD COEF      TOL.     T        P(2 TAIL)

CONSTANT       0.486155     0.104225     0.000000       .       4.664   0.00001
CMTHG2         0.000003     0.000027     0.014596     0.310     0.096   0.92358
PROXIMOR       0.011640     0.004304     0.359730     0.404     2.705   0.00823
LOGSOSW       -0.192519     0.052243    -0.382332     0.663    -3.685   0.00040

ANALYSIS OF VARIANCE

SOURCE        SUM-OF-SQUARES     DF    MEAN-SQUARE          F-RATIO        P

REGRESSION    0.269544            3    0.089848             17.677816      0.0000
RESIDUAL      0.442179           87    0.005083

-----------------------------------------------------------------------------------------------------------
```

REACH JUMP MODEL

>MODEL RJHT = CONSTANT+PROXIMORPHY+LOGSOS$_W$
>ESTIMATE

```
DEP VAR:                                    RJHT
N:                                          91
MULTIPLE R:                                 0.615
SQUARED MULTIPLE R:                         0.379
ADJUSTED SQUARED MULTIPLE R:                0.365
STANDARD ERROR OF ESTIMATE:                 0.070889

VARIABLE    COEFFICIENT  STD ERROR   STD COEF    TOL.    T       P(2 TAIL)

CONSTANT     0.491699    0.086355    0.000000     .      5.694   0.00000
PROXIMOR     0.011947    0.002872    0.369216    0.896   4.159   0.00007
LOGSOSW     -0.195079    0.044699   -0.387418    0.896  -4.364   0.00003

ANALYSIS OF VARIANCE

SOURCE      SUM-OF-SQUARES   DF   MEAN-SQUARE       F-RATIO      P

REGRESSION  0.269497          2   0.134748          26.813981    0.0000
RESIDUAL    0.442226         88   0.005025
```

REACH JUMP MODEL BACKUP

>MODEL RJHT = CONSTANT+(CORRECTED MID-THIGH GIRTH)^2+LOGSOS$_W$
>ESTIMATE

```
DEP VAR:                                    RJHT
N:                                          91
MULTIPLE R:                                 0.571
SQUARED MULTIPLE R:                         0.326
ADJUSTED SQUARED MULTIPLE R:                0.311
STANDARD ERROR OF ESTIMATE:                 0.073805

VARIABLE    COEFFICIENT  STD ERROR   STD COEF    TOL.    T       P(2 TAIL)

CONSTANT     0.484677    0.107898    0.000000     .      4.492   0.00002
CMTHG2       0.000057    0.000019    0.318780    0.689   3.024   0.00327
LOGSOSW     -0.165457    0.053084   -0.328590    0.689  -3.117   0.00247

ANALYSIS OF VARIANCE

SOURCE      SUM-OF-SQUARES   DF   MEAN-SQUARE       F-RATIO      P

REGRESSION  0.232368          2   0.116184          21.329102    0.0000
RESIDUAL    0.479355         88   0.005447
```

APPENDIX F

(Glossary of Biomechanical Terms. Concepts. and Units)

The following terms are defined for the benefit of those who do not have a background in biomechanics.

The definitions are taken from Rodgers and Cavanagh. 1984 (see the Bibliography for the full reference).

For full definitions and descriptions of most biomechanical terms. the reader is directed to this article.

Mass

> "The quantity of matter in an object. Mass can be thought of conceptually as the number of atoms in the object that would. of course. remain constant regardless of location or gravitational conditions (e.g. earth or moon gravity). Weight. however. would vary under these two conditions. The importance of mass in mechanics is that it represents. in linear terms. the resistance to a change of state (a speeding up or slowing down)." (Rodgers and Cavanagh. 1984. p. 1886)

Units: kilogram (kg)

Centre of Mass

> "The point on a body that moves in the same way that a particle subject to the same external forces would move."
>
> (Rodgers and Cavanagh. 1984. p. 1886)

Note:

> "The centre of mass is *not* necessarily located in the body..."
>
> (Rodgers and Cavanagh. 1984. p. 1886)

Synonym: centre of gravity

Centre of Gravity

> "The point at which a single force of magnitude mg (the weight of the body or system) should be applied to a rigid body or system to balance exactly the translational and rotational effects of gravitational forces acting on the components of the body or system. In other words. the point at which the weight of the body or system can be considered to act."
>
> (Rodgers and Cavanagh. 1984. p. 1886)

Note:

> "i. For all practical purposes. the centre of gravity and the centre of mass are coincident. although in strict physical terms. there is an infinitesimal difference between the two.
>
> ii. The centre of gravity of the human body is not fixed at an anatomical location. Its location varies according to the position of the body segments."
>
> (Rodgers and Cavanagh. 1984. p. 1886)

Moment of Inertia

> "The rotational equivalent of mass in its mechanical effect, that is, the resistance to a change of state (a speeding up or slowing down) during rotation. Intuitively, this would appear to be dependent on the mass of the object and the way the mass is distributed. In fact, the effect of distribution of mass is dominant as the following formula indicates:
>
> $$I = m r^2$$
>
> where m = mass and r = distance from the axis of rotation."
>
> (Rodgers and Cavanagh, 1984, p. 1887)

Note:

> "Unlike mass, for which there is only one value, a new value exists for moment of inertia for each new axis that is chosen."
>
> (Rodgers and Cavanagh, 1984, p. 1887)

Displacement

> "The change in the position of a body. This change may be translational, whereby every point of the body is displaced along parallel lines; it may be rotational, with the points of the body describing concentric circles around an axis; or it may be a combination of the two. For example, although the general movement of the human body during locomotion is translational, the limbs act with rotatory motion around many joints to obtain this end result."
>
> (Rodgers and Cavanagh, 1984, p. 1887)

Units: metres (m)

Angular Displacement:

> Results from rotation of an object around an axis, as described above.

Units: radians (rads)

Velocity

> "A measure of a body's motion in a given direction. Because velocity has both magnitude and direction, it is a vector quantity that can be positive, negative, or zero. Linear velocity is the rate at which a body moves in a straight line. Mathematically, velocity is the first derivative with respect to time of displacement and the first integral with respect to time of acceleration."
>
> (Rodgers and Cavanagh, 1984, p. 1887)

Units: metres/second (m/s)

Angular Velocity

> "The rate of movement in rotation calculated as the first time derivative of angular displacement."
>
> (Rodgers and Cavanagh, 1984, p. 1887)

Units: radians/second (rads/s)

Acceleration

"The rate of change of velocity with respect to time, mathematically the second time derivative of displacement and the first time derivative of velocity. Acceleration is also a vector quantity that may take positive, negative, or zero values."

(Rodgers and Cavanagh, 1984, p. 1888)

Units: metres per second per second (m/s^2)

Angular Acceleration

"Angular acceleration refers to the rate at which the angular velocity of a body changes with respect to time. In algebraic form, average angular acceleration is equal to the final angular velocity minus the initial angular velocity divided by the time taken."

(Rodgers and Cavanagh, 1984, p. 1888)

Units: radians per second per second ($rads/s^2$)

Force

"A vector quantity that describes the action of one body on another."

(Rodgers and Cavanagh, 1984, p. 1888)

Units: Newtons (N)

Moment

"The turning effect produced by a force. Calculated as the product of the force and the perpendicular distance between the line of application of the force and the axis of rotation. In vector terms, the calculation is the vector (cross) product of force and distance."

(modified from Rodgers and Cavanagh, 1984, p. 1888)

Weight

"The force that results from the action of a gravitational field on a mass."

(Rodgers and Cavanagh, 1984, p. 1888)

Units: The same as for force, since weight is a force.

Ground Reaction Forces

"The forces that act on the body as a result of interaction with the ground. Newton's third law implies that ground reaction forces are equal and opposite to those that the body is applying to the ground. Ground reaction forces can be measured with a force platform."

(Rodgers and Cavanagh, 1984, p. 1887)