ONTOGENY OF CHILDREN'S LIMBS - WITH PARTICULAR REFERENCE TO INERTIAL CHARACTERISTICS

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BY

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Acknowledgements

At this time, after three years of hard work (life was sometimes hard as well), on the completion of my thesis, I feel, as one of our Chinese proverb goes, "all kinds of feeling well up in my heart". It is impossible to convey all of these feelings. However, I would like try to express one or two.

I would like to express my gratitude to the *Academia Sinica* (Chinese Academy), who has supported me in my study in Liverpool for more than three years, with their limited access to foreign currency.

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SUMMARY

The segment-zone-water-displacement method was used in this study to obtain volume distribution data on limb segments. A mathematical method was then applied to those data to calculate the values for centre of gravity, radius of gyration, principal moment of inertia, and volume. Conventional anthropometric measurements were also undertaken on the subjects. It has been shown that the segment-zone--water-displacement method is not sensitive to random error, and gives a good estimation of inertial properties.

The results demonstrate that some anthropometric variables show pre-adolescent sexual dimorphisms. Allometric analyses reveal that girls undergo more body shape change than boys. At the age of onset of adolescent growth, girls generally accelerate, and boys decelerate, their body shape changes. In both sexes, the proximal end of a limb segment has a higher growth rate than the distal end. As expected theoretically, moment of inertia has a dimension of the fifth power of linear measurement.

Centre of gravity, expressed as percentage of segment length, has a very small variance; the variance of radius of gyration is even smaller. These two variables showed sex-related differences, the former has also displaied difference among ages, especially for multi-segment units such as forearm

with hand. Both centre of gravity and radius of gyration could be predicted from anthropometric variables using regression methods, although the prediction were more accurate for multi-segment limb units than the individual units.

The principal moment of inertia and volume are highly correlated with anthropometric variables so that sound regression equations can be created. Volume ratios have significant sex and age differences, which do not occur with the absolute value for volumes.

Mathematical models for human body segments can be created, which satisfy the required values for length, mass, centre of gravity, radius of gyration, and principal moment of inertia. Such models may prove important in analytical studies of sports medicine and ergonomics.

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1 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES OF THE STUDY

1.1.1 Background

This study has examined the inertia properties (mainly the centre of gravity, principal moment of inertia and radius of gyration) of the limbs of children. These variables are regarded as important by workers in the fields of sports science, ergonomics and medicine. They are also significant in the study of child development because they will respond to the changes in body form during ontogeny.

The changes in body size and shape of children during growth have also been examined using both traditional anthropometry and body inertia characteristics.

The determination of the centre of gravity and the principal moment of inertia have for long been important components of morphological and biomechanical studies. Commencing with investigations undertaken in

Germany at the end of last century (Harless, 1860; Meeh, 1895; Braune and Fisher, 1889; Fisher, 1906), most such studies have used adult cadavers. Important contributions in the field were subsequently made in the U.S.A. (Dempster, 1955a; Clauser *et al* , 1969; Drillis and Contini, 1966) in the middle of this century, but it has taken half century since the work of Zook (1932) and Bernstein *et al* (1931) for the data collection of these variables to be carried out in the context of child development.

Methods employed in such investigations can be divided into two categories: direct and indirect. The former are mainly used on cadavers, the latter are designed to be used on either cadavers, or living subjects.

Direct methods can only be used on a mechanically independent system (for example the whole human body, or a dismembered body part) which can be tested mechanically (by methods such as vibration, balance and so on). Because these methods are usually designed around the exact definitions of the inertia properties themselves, without making extra assumptions, any sources of error are considered to be limited to technical ones.

The indirect methods involve a wide range of techniques, including geometric, dynamic, and mathematical. They were devised in order to determine the biomechanical properties of human body segments *in situ* , in order that data could be obtained from living subjects.

The disadvantage of these latter methods is that several assumptions must be made in order to construct a model for the method. Without exception, every assumption deviates, much or less, from the true situation. System errors are introduced and it is difficult to find a method for testing the dimension of these errors. Partly because of this, it is considered that accurate measurement of the location of centre of gravity on a living subject is very difficult (Roebuck *et al*, 1974).

The determination of the principal moment of inertia of body parts on living subjects is even more difficult. Among the disadvantages of these methods is the fact that it is often impractical to ask a subject to maintain a preferred posture for long enough in order to complete the required experimental procedure.

Although cadavers can be used for the direct methods, they are not considered good representatives of the living body, either in terms of their anatomy, or of their biomechanics (Contini *et al* , 1963; Miller and Nelson, 1976). The sources of cadaveric specimens are also limited. Therefore although indirect methods have disadvantages as previously discussed, they are frequently adopted for the study of inertial properties of living subjects, particularly during the last two decades.

The data concerning inertial properties of human body parts have wide applications. Firstly, the data for the centre of gravity of the body parts may be used to estimate the location of the centre of gravity of a whole body in different positions. Secondly, the locations of the centre of gravity and principal moment of inertia of the limbs are important parameters in physical education, sports, and medicine (eg. the design of artificial limbs).

The radius of gyration and the location of the centre of gravity of the body parts depends on their shape and composition. The principal moment of inertia also additionally depends on the mass density of the body segment. Any differences of body shape and composition among sex or age groups may thus be reflected in changes in these variables. This suggests that there may exist indicators of the developmental pattern by which children grow; such patterns may not be as easy to reveal by the study of other morphological variables.

It is a complex, time-consuming, and potentially expensive task to undertake the determination of the inertial properties of human body segments by existing methods, especially if applied to large sample. However, it is possible for these inertial properties to be statistically correlated with anthropometric variables (Drillis *et al*,1966; Zatziorsky *et al*, 1983, Hinrichs, 1985; Ackland, *et al* , 1988). As a result, these properties may be predicted by regression methods from some relatively-easy-to-measure anthropometric variables.

1.1.2 Objectives

The objectives of this research project were:

1) To develop a refined 'segmental zone' method for the determination of inertial properties of body part on a large sample, the method should be simple, practical and low cost.

2) To study the ontogeny of change during the growth of limbs of children, including size and shape changes and sexual dimorphism. Particular reference is to be made to the inertial properties.

3) To create a database for the locations of the centre of gravity, principal moment of inertia, radius of gyration, and the volume of body parts (eg. the upper limb and calf) of children at and around the age of puberty. These observations have potential applications in the field of sports research and physical education.

4) To examine the relationship between biomechanical variables and morphological variables in order to provide a method of predicting the former from the latter using regression equations.

5) To create a database of auxological development of children in Liverpool area. These new data will be compared with similar data collected within the period 1980-1987. Any changes in growth pattern, such as secular trend, will be investigated.

1.2 DEFINITION OF TERMS USED IN THIS THESIS

1.2.1 Mass centre and centre of gravity

'Mass centre' of a body refers to a point in a mechanical system, at which the mass of the body can be concentrated without affecting the behaviour of the system under the action of external forces. In practical terms, mass centre is coincident with the centre of gravity (which can be explained similarly except that the term 'mechanical system' in the explanation should be replaced by 'gravitational field'). In this thesis, the mass centre (or the centre of gravity) was treated linearly in one dimensional space. It refers to the PLANE which is perpendicular to the main axis of the body part with the POINT of centre of gravity (or the mass centre) on it. In this thesis, the term 'centre of gravity' will be used rather than 'mass centre', even though they were considered to be interchangeable (Hanavan, 1964).

The plane of the centre of gravity may be defined directly as the plane with the sum of the moment of gravity about it on both sides being equal. The centre of gravity of a body is, in fact, a parameter for distribution of gravity on it.

It is apparent from the above definition that mathematically, centre of gravity, is equivalent to the term 'mean' in statistics. For a distribution in one-dimensional space, the centre of gravity can be defined as:

$$CG = \frac{\int_0^l x f(x)\,dx}{\int_0^l f(x)\,dx}$$

or, alternatively for a discontinuous distribution by the formula:

$$CG = \frac{\sum_{i=1}^{n} x_i M_i}{\sum_{i=1}^{n} M_i}$$

Here, f(x) or M_i is the density distribution of mass, CG is the distance from the centre of gravity to one end of the body. It can be observed in this formula that the centre of gravity is a special case of the mean when the distribution is that of mass, or gravity.

In this thesis, when 'CG' for centre of gravity (or 'RG' for radius of gyration) is used as an expression, it refers to the position of the centre of gravity (or the length of the radius of gyration), either absolutely or relatively. However, if its value is quoted, the relative value is always used. Figure 1.1 shows a mass distribution in one-dimensional space and Figure 1.2 represents a simple mechanical model for a limb segment.

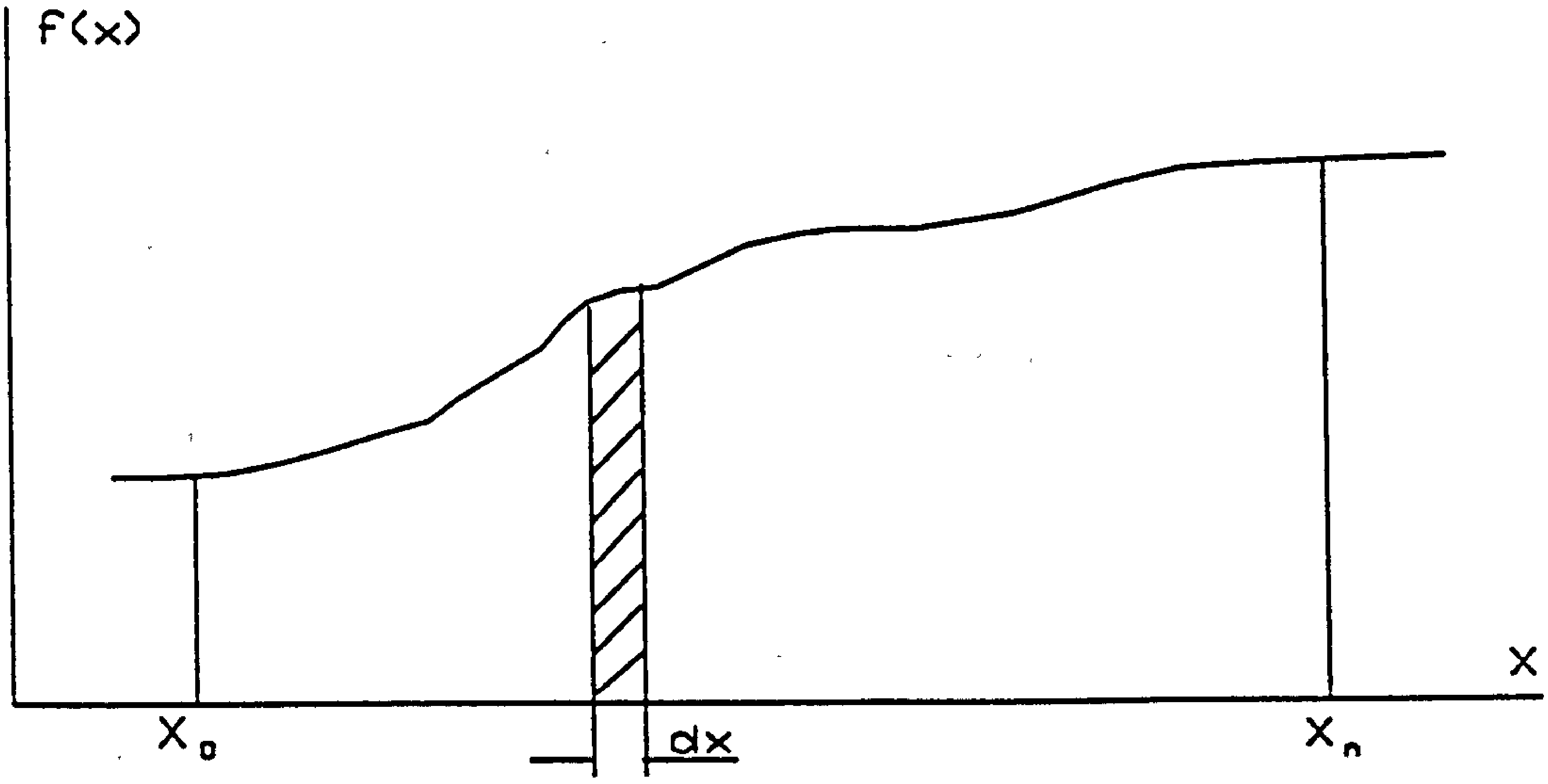


Fig. 1.1 A distribution function.

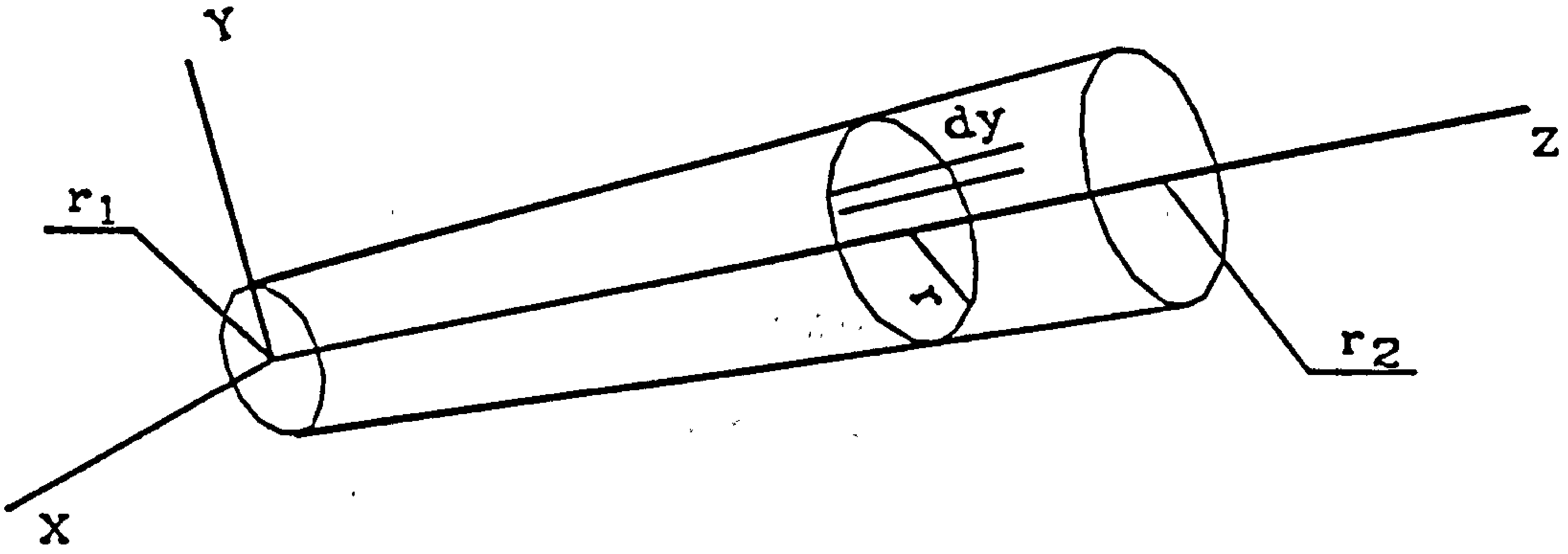


Fig. 1.2 A truncated cone model of the limb.

1.2.2 Moment of inertia and principal moment of inertia

Moment of inertia is an inertial property of a body in angular movement. Being an analogy of mass in linear movement, the moment of inertia resists the angular acceleration of a body. The value of the moment of inertia of a body depends upon not only its mass but also the radius of the circular movement so that it cannot be specified unless the movement is given. As a special case, the ***principal moment of inertia*** refers to the moment of inertia when the axis of circular movement goes through the mass centre. The principal moment of inertia has the minimum value of all the moments of inertia in the same plane.

The value of moment of inertia (MI) of a body can be expressed as:

$$d(MI) = \rho^2 \, dm$$

where MI is the moment of inertia of a particle with mass dm, and ρ is the distance between the particle and gyration axis. As Figure 1.2. shows, the moment of inertia of a round plate with radius r and depth δ_i about axis OX is then:

$$MI_i = 4\delta_i \int_0^r \int_0^{\sqrt{r^2-y^2}} (z^2 + y^2) D_i dy dx = \pi\delta_i(\frac{1}{4} r_i^4 + r_i^2 z_i^2) D_i$$

(D_i is the specific gravity)

So the moment of inertia of the body is:

$$MI = \pi \sum_{i=1}^{n} (\frac{1}{4} r_i^4 + r_i^2 z_i^2) \delta_i D_i$$

The principal moment of inertia is then:

$$PMI = \pi \sum_{i=1}^{n} (\frac{1}{4} r_i^4 + r_i^2 z_i^2) \delta_i D_i - CG^2 M$$

where M is the mass of the limb in question.

1.2.3 Radius of gyration

Suppose that a body with mass m is equally separated into two parts of mass m/2 and the two parts are placed at two sides of the mass centre along an axis at distance ρ. If the moment of inertia of the original body is equal to the sum of the moments of inertia of the two parts of mass (m/2) about the mass centre (the MI of each part being $m\rho^2$), then the length, ρ, is known as the radius of gyration of the body about the axis.

In the same way that the centre of gravity relates to the statistical mean, the radius of gyration also has its equivalent statistical parameters.

The radius of gyration of an object, by definition, and supposing that the diameter of the object is relatively small in relation to its length, could be expressed approximately as:

$$RG = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 M_i - CG^2 M}{M}}$$

which is equivalent to the mathematical concept of the standard deviation. The radius of gyration is therefore a parameter expressing the extent of dispersion of a mass distribution. This will be discussed in detail in later chapter.

1.2.4 Density

Density is used in this thesis in two ways. Firstly, it is a statistical term where the distribution of a variable is considered. For example if a random variable has a distribution function F(x), its density function is:

$$f(x) = dF(x)/dx$$

and its density at point p is $F'(x)|_p = f(p)$.

Secondly, density is also a physical term: it is defined as the mass in a volume unit.

In order to avoid confusion, the first definition is indicated by 'density of distribution', and the second definition, by 'specific gravity' (ie. the weight in a volume unit. On the surface of the earth, its value is essentially the same as that of the 'density', which means the mass in unit volume).

1.2.5 Biomechanical characteristics and inertial properties

These two phrases are used synonymously in this thesis. They imply any of the terms centre of gravity, moment of inertia, radius of gyration, and volume, singly or collectively. Most studies in this field have used the term 'human body parameters' to describe them. Since in this study they are treated as variables, rather than parameters, this term was deemed to be confusing and has not been adopted.

1.3 LITERATURE REVIEW

This literature review is divided into three sections: (i) human body inertial properties, (ii) anthropometry, and (iii) children's growth. Only brief attention is given to anthropometry, which is simply applied as a technique in this study. The literature in area of children's growth and development is extensive (Tanner, 1981). Therefore, only the publications which are closely linked to this thesis in terms of selection of variables or analytical methods (such as literature on the growth pattern of body inertial characteristics), or which use allometric models, are reviewed here.

1.3.1 Studies of biomechanical characteristics

Systematic studies designed to determine the weight, volume, centre of gravity, and principal moment of inertia of subdivisions of the human torso and limbs began in the middle of the last century. Whole human body studies have a longer history, with the earliest recorded work being undertaken in the seventeenth century, when Borelli (1679) determined the centre of gravity of male humans using a platform supported on a knife edge. The subjects were asked to lie down on the platform and by moving the platform until it was balanced, the centre of gravity could be located. This technique was classified later as the 'first class lever' method by Drillis and others (1964).

Most research into human body biomechanical characteristics has been done under the background of ergonomics, or 'human factors'. This area includes the works of Dempster (1955a), Clauser *et al* (1969), Drillis and Contini (1966), Hanavan (1964) and Chandler *et al* (1975). Except for Hanavan, who tried to establish models for the human body and body segments, other authors aimed to determine the parameters of these characteristics (ie. population mean and standard deviation). Realising the difficulties in collecting specimens, much attention was paid to sampling techniques. Generally, the samples were selected rather than chosen randomly. As a compensation, these authors have given detailed accounts of the nature of their samples and have compared supposed populations with their samples, to minimise possible bias.

Jensen (1978), Yokoi *et al* (1985) and Ackland *et al* (1988) determined human body characteristics of living children, with the purpose of applying the data in physical education. An alternative approach is represented by the works of Hatze (1975), Casper (1971) and Brooks *et al* (1973). Their main purpose was to refine the methodology. Hatze (1975) and Stijnen *et al* (1983) designed the mechanical methods to determine the centre of gravity and principal moment of inertia on living subjects. The latter authors have also compared their method with those of others and have evaluated them. Brooks (1973) sought to validate the data obtained from gamma mass scanner by comparing her results with those of other methods.

A brief summary of the works in this field is listed in Table 1.1.

1.3.1.1 Harless (1860), Braune and Fisher (1889), and Fisher (1906).

Harless (1860) was a pioneer of the study of body segment biomechanical variables. He dismembered the bodies of two executed criminals in order to locate the centre of gravity of body segments in the direction of their long axis. In addition, Harless also determined the weights, volumes and specific gravity of 44 extremity segments taken from seven corpses. Three adult male cadavers were used by Braune and Fisher (1889) to determine the location of the centre of gravity. A number of technical improvements were made in this study. Firstly, the specimens were kept frozen throughout the process so that body fluid losses were reduced to a minimum. Secondly, instead of using a balance, thin but strong rods were inserted into the tissue and the segments were hung in different ways. The three dimensional position of the centre of gravity was then found at the junction of the three hanging planes. In a further study in 1906, Fisher stated that the radius of gyration of the limbs oriented perpendicular to long axis of the limb was about thirty percent of the segment length.

1.3.1.2 Meeh (1895)

Meeh (1895) was a pioneer of investigations involving body part parameters in living subjects. He was also interested in the growth pattern of human body segments. Because his subjects were living, Meeh could not define the boundary of the segments in the way adopted by Harless. In fact, as some later studies have revealed (Dempster, 1955a; Drillis *et al* , 1966) definition of body segments are particularly difficult in living body. By Meeh's definition, all boundaries between segments in the lower limb and trunk were horizontal. Ten living adults (eight males and two females) and four infant cadavers (two males and two females) were investigated and a cross-sectional growth curve obtained.

TABLE 1.1 Summary of main works on human body inertial property						
	Centre of gravity			Moment of inertia		
Author	**Subject**	**Method**	**REG.**	**Subject**	**Method**	**REG.**
Harless (1860)	C	Balance board	N			
Braune (1889)	C	Hung	N			
Fisher (1906)	C	Hung	N			
Bernstein (1931)	L	Unknown	-			
Weibuch (1933)	L	Contour maps	N	L	Contour maps	N
Dempster (1955)	C	Balance board	N	C	Pendulum	N
Drillis (1966)	L	Water displacement	N	Cast	Compound pendulum	N
Clauser (1969)	C	Balance	Y			
Hatze (1975)	L	Oscillation	N	L	Oscillation	N
Chandler (1975)	C	Photographic Suspension	Y	C	Oscillation	Y
Zatziorsky (1983)	L	Gamma-ray scanning	Y	L	Gamma-ray scanning	Y
Stijnen (1983)	L		Y	L	Release	Y
Jensen (1978)	Children (L)	Ellipse Assumption	Y	Children (L)	Ellipse Assumption	Y
Yokoi (1983)	Children (L)	Ellipse Assumption	Y	Children (L)	Ellipse Assumption.	Y
Ackland (1988)	Children (L)	Ellipse Assumption	Y	Children (L)	Ellipse Assumption	Y

This table shows the most important works in the field of human body segment inertial property (L: Living Subject; C: Cadaver; REG: Regression).

1.3.1.3 Bernstein et al (1931)

Bernstein *et al* (1931) undertook an investigation on 152 living subjects (76 males and 76 females) in order to obtain the mass of their body segments and the locations of their centre of gravity. The original paper is not available and citations of this work are therefore secondary. Some of the results of the study were later described by Bernstein (1967) and it is only from this source that a summary of Bernstein's research can be obtained.

Bernstein's sample had a wide age range (from 10 to 77). His analysis did not include determining the location of the centre of gravity of the hand and foot. Using frozen cadaver segments, Bernstein concluded that the centres of gravity of human body segments, for most practical purposes, coincide with their centres of volume. This is a basic assumption made in indirect studies of body inertial characteristics on living subjects in a number of investigations during the last fifty years (Weinbach, 1938; Cleveland, 1955; Drillis and Contini, 1966; Jensen, 1978; Ackland *et al* , 1988).

Unfortunately Bernstein's methods are not detailed, but there is evidence that they were relatively sophisticated. Bernstein stated that "it is impossible to present in this chapter even a brief account of the complicated and delicate method employed by the author and his colleagues for measurements of this type. It can only be said that the problem is ultimately related to the planimetric measurements of the volumes and volume moments of the limbs of body and to the weighing of the subject in numerous carefully determined controlled positions on special twin-support scales" (Bernstein, 1967, pp. 10-11).

There are two important aspects of Bernstein's investigation. Firstly, it is the first study, and still one of few, in which not only the mean, but also the standard deviation of the locations of centre of gravity and body segment weight were reported. Secondly, both males and females, and different ages were treated separately. Bernstein's statistics for the centre of gravity estimates are shown in Table 1.2.

Contrary to expectation, Bernstein did not find significant differences in the location of the centre of gravity between the sexes. Bernstein gave no indication in his publication whether age had an affect on the locations of the centre of gravity. But, from data quoted by Drillis and Contini (1966), it seems that there was no change in this variable for the different age groups.

Table 1.2 Centre of gravity determined by Bernstein

Segments	Male	Female	SD*
Thigh	38.57	38.88	3.32
Lower leg	41.30	42.26	2.24
Upper arm	46.57	48.40	3.38
Forearm	41.24	41.74	3.09

* For pooled sex sample

1.3.1.4 Zook (1932)

Zook (1932) measured body part volumes of 164 boys from 5-19 years of age. His equipment consisted of a water tank, a platform hung on a wire, and a graph recording system. The subjects were asked to stand on the platform which was lowered, step by step, into the tank. The water in the tank was displaced out into either of two cylinders from which the volume was measured. This volume was recorded on a board by a pen fixed to a conical brass float. The water was then released to another container and the accumulated volume of the displaced water recorded.

Zook measured the volumes of subjects from the sole to the top of head. He selected a number of landmarks on the body surface in order to define the boundaries of the segments. In this way, the volumes of feet, calf, thigh, loin, abdomen, chest, neck, and cranium were measured; about eight minutes were needed to measure each subject.

The subjects in this study were divided into two groups: 'university', recognised as a well-nourished population, and 'settlement', whose members lived on poor food and were provided with inadequate care.

Zook did not use the data obtained to locate the centre of gravity, even though this would have been possible. A series of comparisons of the volumes of the university and settlement groups was made, using different age ranges. The growth pattern throughout the age distribution, especially at around puberty, was also discussed. Zook made a number of proposals for possible improvement and extension of his method, which include the design for an apparatus to determine the specific gravity of living subjects.

Zook had well-designed equipment, measured a large number of subjects, and undertook limited analysis of his data. However, the statistics and sample design aspect of the work can be criticised. Firstly, the sample size of each age group in his study ranges from one to twenty two. Secondly, except for using sample means, he did not use any statistical method to analyse his data. He made conclusions about growth patterns from some age groups which had only one, two, or three subjects.

1.3.1.5 Weinbach (1938)

Weinbach (1938) used a contour map technique in order to calculate the location of the centre of gravity and principal moment of inertia of the human body. By supposing that cross-sections of human body are elliptical, Weinbach obtained the maximum and minimum axes of each cross-section by means of either direct measurement or the use of two photographs, one a front view, the other a side view. The area of ellipse equals 3.14 times the product of the lengths of its two half axes, and a contour map of the subject could be drawn from the data obtained.

The centres of gravity and the moments of inertia of the subjects were located from these contour maps. Weinbach did not use his data to calculate the value for the individual body parts, even though it would have been possible. Due to the difference between the assumption that cross-sections of the human body are elliptical in shape and the true situation where they are not, inaccuracy is inevitable in this experiment. However, considering the technical difficulties of getting accurate cross-sectional area of living human bodies at that time, it should be said that Weinbach's method was both innovative and useful. In fact, his methods were still being used in recent studies (Jensen, 1978; Yokoi *et al,* 1985; and Ackland *et al,* 1988).

1.3.1.6 Cleveland (1955)

Cleveland (1955) investigated the location of the centre of gravity of living body segments, and published his findings in a Ph.D thesis, but it has proved impossible to obtain a copy of the thesis. However, information relating to the technique used by Cleveland (1955) has been published in a book (Miller *et al,* 1976), and has been detailed by Clauser *et al* (1969).

In Cleveland's study, the subject, resting on a hammock, was measured twice by a spring scale on which the hammock was fixed. Firstly, the subject was measured in the air and then certain parts of the body was immersed in water and remeasured. Cleveland called the average of the two readings 'centre of gravity weight'. He believed that by adjusting the height of the hammock above water until the reading on the scale is exactly the 'centre of gravity weight', the centre of gravity of the body part in question must lie on the plane of the water surface.

Unfortunately, Cleveland did not take sufficient notice of the fact that he was dealing with two closely related, but different concepts. The first is the average, or mean, and the other is the median. Generally speaking, the mid-point and centre-point of a distribution are not coincident, except for special cases such as a symmetrical distribution. The 'median', or middle point, separates a distribution equally on its two sides, as in Cleveland's work. In other words, there would be the same volume on both sides of the median. However, because of the irregular shape of the human body, the median would not always be at the centre point since it depended not only on the amount of the elements but also the moment of the elements.

From the definition of Cleveland's 'centre of gravity weight', it is apparent that Cleveland located the mid-point, but not the centre, of the volume. Because all human limbs have a similar biased volume distribution pattern (proximal being bigger than distal), it is easy to predict that the middle point would be more proximal than the centre point.

A triangle model could be used to illustrate this. For a right-angled triangle with right angle at the (0,0) of coordinates and an adjacent side with unit length on the X axis. The centre of gravity of this triangle along X is $1/3=0.333$, while the mid-point is $1-\sqrt{2}/2=0.293$.

Moreover, as stated earlier, the assumption supporting the indirect method is that the parameters of volume can be used to determine those of weight. That is, the specific gravity of the body part is the same everywhere, so that the centre of gravity is coincident with the centre of volume. In fact, the specific gravity of the distal end of a limb is always greater than that of proximal end because the ratio of bone/soft tissue is greater distally (Dempster, 1955a). Thus, the estimated location of the centre of gravity based on this assumption would be somewhat more proximal than it would be in practice. Unfortunately, since the systematic error attributed to Cleveland's method was in the same direction as that directed from the basic assumption, an accumulated error was unavoidable.

In conclusion, it is considered that Cleveland's method did not, and could not, give a satisfactory solution to the location of the centre of gravity, either in practice, or in theory.

1.3.1.7 Dempster (1955)

Dempster (1955a) studied human body segment biomechanical variables. Ten cadavers were employed for measurement (seven un-preserved and three preserved); in addition, 39 carefully-selected men were measured as a supplementary sample. The subjects were submitted to 69 anthropometric measurements and their physique was characterised.

Dempster's work has been widely quoted for two reasons. Firstly, the variables measured were more comprehensive than in earlier studies and included weight, volume, centre of gravity, specific gravity, moment of inertia of body segments and the movement centres of joints. Secondly, the cadaver sample doubled the number used previously by previous scientists.

In addition to conventional anthropometric measurement, the volumes of limb segments were determined by the immersion method. In order to do this, several boxes of different size were designed to measure the extremities. Each box was surrounded by a circular trough which was used to collect the water displaced from the box by the limb. The volume of the limb in question was then determined by weighing the water displaced from the box and collected in the trough.

The principal moment of inertia of body parts was determined by a pendulum method. A metal tube was inserted into the body segment under study and the two ends of the tube then mounted on a knife edge system in order that the body segments could swing freely. The time taken for ten periods of the pendulum was recorded and the frequency then calculated.

The moment of inertia of the segment about the axis presented by the metal tube I is:

$$I = \frac{WL}{4\pi^2 f^2}$$

where W is the product of the mass and the gravity acceleration (g, 980 cm/sec^2), L is the distance of the centre of gravity to the axis of the pendulum, f is the frequency of the system. According to the Parallel Axis Theorem, the principal moment of inertia, I_o, was calculated with the formula:

$$I_o = I - \left(\frac{W}{g}\right)L^2$$

In determining the value of body segment variables, Dempster carefully dismembered the cadavers. He recognised that "since segments are in fact continuous, any separation of segments is arbitrary",but he endeavoured to define the segments as reasonably as possible. He believed that when joints are set in the middle of their movement range, the soft tissue around the joints are most equitably distributed. Accurate dissection was achieved by fixing joints in mid-range and then freezing them locally with dry ice. The centre of gravity of each segment was determined with a balance plate.

As Dempster realised, even his 'larger' sample had its limitations, for it represented individuals of the older segment of the population, and it is below the average of the population in both stature and weight. However, this study is still one of the best sources of data on human body inertial characteristics to date.

1.3.1.8 Swearingen (1962) and Swearingen and Young (1965)

Swearingen (1962) designed an apparatus used to determine the centre of gravity of the whole body. The equipment was composed of five platforms mounted one on the top of the other in such a way that the reading of the centre of gravity was not affected by the position of the subject on the topmost platform. The best accuracy could then be obtained. Five subjects were measured in 67 body postures with a further twenty-seven tested in the standing and sitting positions. Later, in 1965, Swearingen and Young tested the centre of gravity of children aged from 5 to 18 years in standing and sitting postures.

Swearingen did not examine body segment variables. But his equipment, a good, refined, reaction-board (classified by Drillis as a 'second class lever'), was used later by Clauser *et al* (1969) to determine the centre of gravity of human body segments.

1.3.1.9 Santschi et al (1963)

Santschi *et al* (1963) conducted a study to determine the principal moments of inertia and the centre of gravity of 66 living, male, subjects. Their method was based on the principle of the compound pendulum.

1.3.1.10 Fujikawa (1963)

Fujikawa (1963) located the centre of gravity of body segments of cadavers. This study was unusual in that it used subjects from a country outside Europe and U.S.A. The head, trunk, hand and foot were tested by hanging at two points. The centre of gravity was located along the cross-line of the two vertical planes determined by the hanging points. The centre of gravity of the arm and leg were determined when the specimens were balanced on a bar and the position of centre of gravity was indicated by the bar. Just five cadavers were used in the study, and the methodology was crude.

1.3.1.11 Clauser et al (1969)

Clauser, McConville and Young (1969) made a comprehensive study of the physical characteristics of the human body, The aims of the study were to: a) obtain data on body parts based on a more representative sample than previous work; b) validate some unproved assumptions, such as those of Bernstein, in which it was assumed that the centre of volume and the centre of gravity are coincident with each other; c) create, if possible, a series of regression equations with which human body parameters could be estimated from easier-to-obtain anthropometric variables.

By comparing the means as well as the correlations between variables of a living population and their cadaveric sample, Clauser *et al* sought to show that their sample was representative. The sample was carefully selected based on criteria presented in descending order of importance. These were: 1) age at death; 2) overall physical appearance; 3) evidence of debilitating diseases or accidents before death; 4) body weight; 5) stature.

Because of adherence to these strict criteria, it was impossible to obtain sufficient suitable fresh cadavers so preserved cadavers were used to overcome this difficulty. Clauser and his co-workers believed, from studying Fujikawa's work (1963), and from a personal communication from Dempster, that formalin-alcohol injection had very little influence on the ratio of weight of each body segment to the whole body weight. They also believed that the loss of tissue fluids did not affect the location of the centre of gravity significantly. The human cadavers selected were subjected to detailed anthropometry. If there was any difficulty in locating the landmark on body surface, X-ray and fluoroscopy, or even dissection, was used.

A method similar to those used by Braune and Fisher (1892) and Dempster (1955a) was used to dismember the specimens. Not every cadaver joint was placed in its mid-range since the tissue could not be stretched sufficiently. Severing the tissue ran the risk of losing body fluids from the specimen. A full description and illustration of the detailed methods used to dismember cadavers was provided.

The equipment designed by Swearingen (1962) was used to locate the centre of gravity of the whole body and of each dismembered body part. Appropriate statistical methods were applied to the data obtained. Fourteen cadavers were measured, but only the latter 13 were used as the basis for statistical analysis; the first cadaver was used to test the dismembering and measuring techniques. Particular attention was paid to details of measurement technique and statistical methods. Any items considered unreliable or non-standard were eliminated from the final analysis to avoid bias in the results.

Using a stepwise regression method, a series of regression equations were created with one, two, and/or three anthropometric variables used to predict the values of the body segments. Instead of employing the traditional method, in which maximum length is used, the distances between certain landmarks (which are easily to define and locate on living subjects) were used as the independent variables in the prediction equations. It was concluded that anthropometry of the body can be used effectively to predict the weight and the location of the centre of mass of body segments.

However, Clauser *et al* apparently misunderstood Bernstein's assumption (1931) about the centre of volume and centre of mass. In fact, Clauser and his co-workers shared the same misconception as Cleveland (1955), though they did not use it as the basis of their study. As a result, their evaluation of the concepts and results of Bernstein *et al* (1931) and Drillis and Contini (1966) in their Appendix B, was irrelevant.

1.3.1.12 Drillis and Contini (1966)

Drillis and Contini (1966) undertook a study in which the centre of gravity of living body segments was located. The subjects were 12 male students in New York University, aged from 20-39. The authors considered that the most important body segments to study were those of the limbs. They used a refined segment-zone-water-displacement method on living subjects in order to carry on their research. Other methods were also discussed in their paper.

Their equipment consisted of two cylinders. One was used to supply water, being set higher than the second which was used to receive water and measure the limb. The subject's limb was put into the second cylinder in a comfortable position in order to maintain a steady and relaxed posture during the period of measurement. Water was then allowed to flow out from the first cylinder into the second. Two readings were obtained, one was the water decrease in the first cylinder and the other the water increase in the second caused by inflow of water plus the part of the limb which was submerged in water. The difference between the two readings was the volume of the limb segment in question. By repeating this procedure a series of readings was obtained which represented the accumulated volume of the limb. The authors obtained data for the upper limb, thigh, and calf; data for the foot were not obtained by this method. A further study was undertaken in which the casts of the human body were used.

In their data collection using the water displacement method, Drillis and Contini realised that the living human subject is not constant over any long period of time. Variations occurred in the volume and volume distribution over the segments from one experimental session to another.

1.3.1.13 Chandler et al (1975)

Chandler *et al* (1975) undertook analysis of the principal moment of inertia of human body segments. Firstly, the principal moment of inertia in an ellipsoid was defined; this was called the 'ellipsoid of inertia'. A parallel transform coordinate system was introduced into the ellipsoid equation which was an analogy of the parallel axis theorem for moment of inertia. Secondly, the theory of an expression of the principal moment of inertia measurement was established based on the ellipsoid.

The specimens used in the research were six male cadavers selected by their physical condition. Specimens showing congenital abnormalities, evidence of major surgery, structural atrophy, excessive wasting, or obesity were excluded. The cause of the death of all the subjects was cardiovascular.

The weight and stature of the specimens were measured and the Ponderal Index ($S/\sqrt[3]{W}$) was calculated. This index, along with visual observation, was used to classify the specimens into three pairs of similar body build. One cadaver from each pair was measured in the standing posture while the other in the seated posture.

After anthropometric measurement, techniques similar to those employed by Clauser *et al* were used to dismember the cadavers. However, the method employed to dissect the neck was unique. The separation of the neck and head was defined not by one plane as in previous studies, but two. One was a transverse plane taken at the height of occiput, cut from the posterior neck surface, while the other started at the anterior neck surface, tangential to the mandibular angle, and terminated by intersecting the first plane. The authors believed that defining it in this way, the neck could be considered a functional part of the torso.

Before the dissection, the specimens were fixed onto a standing, or seated, specimen-positioning board in order to achieve the best segmentation result.

Three tick marks were made on each segment-separation line so as to define the segmentation plane. During the dismemberment, the specimens were kept frozen.

The oscillation technique used by Reynolds (1974), one of the co-authors of this paper, was adapted to measure the principal moment of inertia. A series of specimen holders were designed for the different segments and great attention was paid to the accuracy of both the experiment and the analysis of the results. In addition to selected standard anthropometric variables, the principal moment of inertia in three axes (I_{xx}, I_{yy}, I_{zz}), the direction angles of the principal moment of inertia in their three dimensional coordinates, and the regression equations of the segment weight and principal moment of inertia from the body weight, as well as the segment volume, were reported in this paper. In terms of methodology, this analysis can be considered as one of the most rigorous in this field.

1.3.1.14 Hatze (1975)

Hatze (1975) devised a new method for measuring the locations of the centres of gravity and the moments of inertia of human body parts *in situ* so that it could be applied to living subjects. His technique utilised the theory of small damped oscillations in a system about its equilibrium position. The limb under investigation was rested at its proximal joint and hung on a spring at its distal end. When the limb is released from its original position, it oscillates in turn by the force of gravity and spring elasticity. A series of variables describing this damped oscillation system can be pre-determined or measured, and hence the location of the centre of gravity and principal moment of inertia can be calculated. Hatze considered his method to be highly reproducible, and requiring only simple equipment.

1.3.1.15 Casper (1971) and Brooks (1973)

During the seventies, imaging techniques have been introduced into research investigations of the body segment analysis. This method is basically a segment zone method, but in order to obtain cross-section areas, or segment volumes, the traditional immersion methods (eg. Drillis and Contini, 1966), or the elliptical zone modelling (eg. Weinbach, 1938) are replaced by gamma mass scanning. This method has several advantages. In addition to cross-section area being more accurately estimated, the data for specific gravity of each limb section is also obtainable. The error which can arise from the difference between gravity and volume does not exist since in this method the assumption of identical density of body segments is no longer needed.

Casper (1971) and his colleagues carried out several studies using this method. Brooks (1973) sought to validate the gamma mass scanner for the determination of the centre of gravity and principal moment of inertia. In this study, reaction board, gamma ray, immersion and pendulum methods were all applied to three lamb legs and three trials were made for each different method. By comparing the individual trials with their average and comparing the results from each of the methods with that of reaction board, which was believed to be the most reliable, Brooks found that the gamma scanner gave the results with the smallest errors.

1.3.1.16 Zatziorsky and Seluyanov (1983)

Zatziorsky and Seluyanov determined the mass and inertial characters of living body segments with the gamma scanner technique. One hundred human subjects, mainly students, were subjected to gamma scanning in this study and the means and standard deviation of mass and inertia characteristics of body segments were reported. The age, height, weight and circumference of the chest of the subjects are provided. Regression equations for the centre of gravity of the limb were then generated. When height and weight were included in the equations the resulting correlation coefficients were in the range 0.2-0.6.

1.3.1.17 Stijnen et al (1983)

Stijnen *et al* (1983) investigated the principal moment of inertia of human body extremities *in situ* by a modified release method. Thirty four students of physical education were tested. A force transducer was used to measure the joint axis. The moment of the segmental weight about the axis was expressed as M = -F.

The segment was positioned approximately 10 degrees above the horizontal plane and then released quickly. The tangential acceleration (a) at the centre of percussion of the segment was recorded by an accelerometer during the first 0.5 second of the movement. The acceleration-time curve was evaluated visually on an oscilloscope and a judgement of whether or not the limb had been relaxed when the test was made. Any subjects who were considered not to have relaxed their muscles were asked to repeat the test. The principal moment of inertia of the limb in question could be expressed as $I = M \times r/a$. Where r is the distance between the axis and the point on which the accelerometer was fixed.

A second test was carried out on the same subjects using Hatze's pendulum technique (1975). The test-retest result showed that the release method was highly reproducible. The correlation coefficient of the two results were 0.96 for whole leg; 0.87 for forearm plus hand; 0.91 for the shank plus foot and 0.93 for the whole arm. Statistical analysis showed that a significant difference existed between results obtained in this study and those reported by Dempster (1955a), Hanavan (1964) and Hatze (1975).

Stijnen found that the results of Hatze's pendulum method were affected by two variables within the system. These were suspension points and spring constants, which were not recognised by Hatze. Stijnen pointed out that increasing the distance between the joint axis and suspension point, or increasing the spring constant could increase the estimated moment of inertia.

1.3.1.18 Hanavan (1964)

In addition to the different experimental methods outlined above, a mathematical model of human body and body segments was proposed by Hanavan (1964). This study was based on the principal assumption that the human body can be represented by a set of rigid bodies of simple geometric shape and uniform density. To predict mass and inertial properties, twenty five standard anthropometric dimensions were used in the model.

1.3.1.19 Jensen (1978)

Noticing that the adult parameter cannot be extrapolated and most of the anthropometric data on children are of little or no use for determining inertias, Jensen (1978) undertook an analysis of the body segment mass and radius of gyrations in a sample of children. His basic assumption was similar to that of Weinbach (1938), ie. that human body segments have an elliptical cross-section whose major and minor axes can be determined experimentally.

Jensen used a mixed-longitudinal design in this study. The subjects were 12 boys representing three body types and four age groups. The initial ages of the subjects were 4, 6, 9 and 12 years and the experiment continued for three years; the sample covered an age range from 4-14. The subjects were asked to change into a small nylon bathing suit, and wear a close-fitting swimming cap. The subject was positioned and the joints between body segments were marked. Then, photographs for the frontal and profile were taken. Using Weinbach's (1938) assumption, the values of mass, radius of gyration and the location of the centre of gravity were calculated and regression equations of these variables against age obtained.

The author believed the method to be accurate. This was judged by comparing the estimated total body mass with the direct measured mass. The mean error was 0.203% with a standard deviation of 2.30%.

1.3.1.20 Ackland et al (1988)

With the aim of creating a data set for biomechanical characteristics of children and adolescents, Ackland *et al* (1988) carried out an investigation on 13 male subjects from the competitive swimming and tennis player sub-populations.

Ackland's method to determine the mass distribution was derived from that of Jensen (1978), in which the data were collected for the body segments of leg, thigh, lower trunk and upper trunk. This technique, with additional conventional anthropometric measurements, was applied to subjects at six monthly intervals for five years. Commenting the results, Ackland *et al* showed that there is only a very weak relationship between the independent (anthropometric) variables and estimates of the location of the centre of gravity for all the body segments studied. They considered that the variance of the centre of gravity was so small that further regressions were unnecessary. However, their resultant variances are evidently smaller than previously reported (Bernstein *et al,* 1931).

Believing that Jensen's regression (Jensen, 1986), in which only the chronological age was used as independent variable, was inappropriate for practical use, the authors created new regression equations based on their own data with no more than five anthropometric variables in the predicting equation.

1.3.2 Anthropometry

It has been wrongly reported (Damon and McFarland, 1955; Ross *et al,* 1980) that Quetelet, a Belgium statistician, invented the term 'anthropometry', and established it as a scientific discipline. In fact, the word 'anthropometry' was used before Quetelet. Elsholtz, a German physician, published his book entitled 'Anthropometria' in 1672, and thus marked the establishment of this branch of anthropology (Elsholtz, 1672).

Anthropometry, as technology, rather than science, has undergone great changes during its history and has also played an important part in the development in fields such as anthropology, statistics, medicine and ergonomics (Damon and McFarland, 1955; Ross *et al,* 1980).

An important feature of anthropometric data is their property of comparison. This is because the data have been collected world-wide by different anthropometrists. Standardisation and reproducibility are also essential for such data. Martin and Saller (1957) made a major contribution to anthropology, partly because they unified the measurements and numbered them so that they could be used universally without confusion. The methods in their book, 'Lehrbuch der Anthropologie' are widely adapted as an important, or even standard, reference.

Today, anthropometry is a multidisciplinary subject. It is applied in biological anthropology, either on bones or on living subjects, ergonomics, human biology studies such as children's growth.

1.3.3 Child growth

Research on human development and growth has been undertaken throughout the world (Tanner, 1981). However, there are a number of limitations to much of this work. Firstly, the selection of variables was mainly focused on traditional anthropometric measurements; inertial characteristics have been rarely employed as an indication of growth (Jensen, 1987). Secondly, most studies have examined the relations between individual growth parameters (for example, the anthropometric variables) and age. These are 'univariate studies', and include simple statistics and ratios, based on age groups. This type of study is established either to create growth standards for a population, or to compare one population with another, or simply to understand the growth pattern, or status, of a population. In summary, the interest is concentrated on the population and not the variables themselves.

However, a new facet of research on human development has emerged in recent decades. The principle of allometry, which is the study of differential growth has been used on a wide ranges of organisms, both plant and animal, since Huxley first proposed it in 1924. But there have been few studies applying this idea to relative limb growth during human ontogeny.

1.3.3.1 Meeh (1895)

Meeh (1895) was the first investigator to examine the growth patterns of inertial characteristics of human body parts; the method used has been mentioned in section 1.3.1.2 in this thesis. His subjects consisted of eight living males aged from 12 to 56 years, two living females aged 16 and 22, and four cadavers (one male and one female neonate, one boy aged 1 year 10 months and one prematurely delivered girl).

Cross-sectional growth curves for both sexes were constructed from the data obtained but the conclusions from this data set was not very reliable because of the extremely limited sample number. However there is little doubt that from Meeh's results, it can be observed that proportionally, the volumes of the lower limb increase at a greater rate than those for the upper limb. For each limb, during growth the proximal segment showed a greater volume increment than the distal.

1.3.3.2 Zook (1932)

Zook (1932) measured 160 boys aged from age 5 to 19. He found that in this age period, the leg accounted for about 50% of the volume of the whole body with little change, However, leg length increased throughout the period covered by the cross-sectional sample. In contrast, both the volume and length of the trunk were maintained constant.

Zook found that allometry existed in the growth of segment volume. It was observed that the trunk had its first growth spurt at aged 9 years, at which time the head and leg were growing at a minimum velocity. Later, at about aged 12 years, head and legs reached their peak velocity while the trunk was beginning its second spurt, which would reach its peak by aged 15 years. Zook did not measure the arm separately from the trunk.

In examining the growth patterns of the sample, Zook's data show that the settlement group (the presumed less well-nourished group) presented a significant growth lag (very small growth velocity) at an age over 10, which was then followed by a sharp spurt. This was not shown in the university group (considered to be a better nutritionally-treated group). Zook believed that individuals in the university group also had this growth lag and spurt but they were obscured by each other's compensations because of variations among the individuals within the group. If Zook's findings are correct, the significant growth lag and spurt in the settlement group suggests that poor living standards are a critical factor in affecting the growth of segment volume.

Zook also found that the leg volumes in the settlement group, especially in the younger subjects, were high in proportion to that of whole body, and he also noted that the lag, and subsequently the adolescent spurt mainly took place in the thigh.

1.3.3.3 Jensen (1978, 1981, 1986, 1987)

Jensen stated: "The most commonly used growth parameter, stature, is unidimensional and therefore provides very limited information. Multidimensional parameters, including shape, volume, mass and moments of inertia, should be used to provide a more complete picture of growth." (Jensen, 1987, p. 173). For this reason, he undertook a series of studies of the growth of children's inertial characteristics which he believed could provide important information about children's growth and with application to sports science. The studies were based on a mixed longitudinal data base composed of subjects aged from 4 to 16 years.

Jensen (1986) studied the growth of segment masses in proportion to whole body mass and the segment radius of gyration in proportion to segment lengths, in the context of linear regressions of these variables on chronological age. He found that the mass ratio of the head showed little change during this growth period (b=-0.0006), while the trunk decreased (b=-0.014), and the limbs increased their mass ratios. Within the upper and lower limbs, the distal segments, of say, the hand and foot, had least change (b is -0.00003 for hand and 0.00015 for foot) while the proximal segments had the greatest increases (b is 0.0084 for upper arm and 0.0038 for thigh). It was also found that the radius of gyration showed little change with age. In 1987, Jensen re-examined his sample using a higher-dimensional regression method. He used his longitudinal information in order to examine the maturation status of each segment at different ages. It was found that in most cases the mass maturation of limb segments had the same gradient as that indicated by the length, ie. the distal ends were advantaged (Tanner, 1962). However, there was little difference between upper arm and forearm. Jensen found that the differences between length and mass percentages are not simple cubic differences, suggesting an allometric growth pattern. In 1981, Jensen used his data set to analyse the difference of body mass distribution in three kinds of somatotype, at different ages.

1.3.3.4 Yokoi et al (1985)

Yokoi *et al* (1985) undertook a study of body inertial characteristics on Japanese children (93 boys and 91 girls, aged from 5 to 15 years). This is the largest reported sample, and the only non-Caucasian living population, studied in the area of human body biomechanical variables. The authors found in this study that the biomechanical variables differ between sexes and change with age. After the age of 9 years, girls had a greater mass ratio for the thigh, and the centre of gravity of the thigh was closer to the proximal end, than boys. These differences are also found in older children relative to younger children. Yokoi and his colleagues did not addressed the question as to whether the higher values of these characteristics in girls was due to their greater physical age (earlier adolescence) or whether it was due to other reasons. However, they were the first to identify this difference in human populations. In addition, they also found that fatter children possess a greater radius of gyration for their limb segments than the thinner ones.

1.3.3.5 Thompson (1938)

Thompson (1938) introduced the concept of allometry, or as he called it, relative growth, into the study of human growth. Thompson's data included 46 male and 53 female infants aged from 8 to 56 weeks. He calculated the relative growth rates (ie. the allometry coefficients) of head circumference, thorax circumference in relation to 'the body as a whole'. The exact explanation of what this latter variable was is not specified in the paper. His results indicated that all of the three variables had different values for the rate of growth in different age periods.

1.3.3.6 Marshall et al (1980)

Marshall *et al* (1980) used a longitudinal anthropometric data set of boys aged from 7 to 16 years for an allometric analysis. First, a interpolation method was used to shift the raw data to exact age values. Then, the data of each group were fitted into the regression equation $\log y = k \log x + \log a$ (for allometric equation $y = ax^k$), and the constant k of each age group was determined, with x, the 'size' variable, represented by stature. It was considered that in such a growth study, stature was better than the body weight as 'size' variable because it did not decrease against the time scale.

Some interesting findings were reported in this paper, but it is not without several drawbacks. Firstly, the regression used to describe allometry was calculated using the least square method. The least squares regression method is considered the best way of predicting the value of a variable. However, the least squares slope is affected not only by the ways of the correlation between the two variables, but also by the level of the correlation. For this reason, other regression methods, either geometric mean (or called the reduced major axis), or major axis, have been recommended by some authors in allometric analyses (Ricker, 1973). Secondly, the correlation coefficients were not published, so that an evaluation of the allometric changes in different groups is difficult, if not impossible. The standard error of the slopes provided by the authors suggest that the results of this work should be used only with great care.

1.3.3.7 Hattori (1975) and Vajda et al (1980)

By making the assumption that an allometric coefficient has different values at different development stages of growth, and using a sample of Japanese children aged from 6 to 14 years, Hattori (1975) undertook a study investigating the ways in which the allometric coefficient changes. Hattori used stature as the indicator of growth and divided the sample into two sections: from 115 to 127 cm (aged 6 to 9 years), and from 138 to 154 cm (aged 10 to 14 years).

It is an acceptable practice to divide the sample into different growth levels. However, it is unreasonable to create an artificial line which divided the sample and then compare the allometric coefficients of the age groups in the same division. This is because it will upset the random nature of the samples, especially for any age groups lying close to the division line. For example, a child aged 10 years with a stature 138 cm will very probably have a different end stature and growth status from a child aged 10 but with a stature of 130 cm, or a child aged 12 with a stature of 138 cm.

Like Marshall (1980), Hattori also calculated his allometric coefficients by the least squares method and this affects the validity of his results for the reason previously stated. However, there are interesting findings in the study. The allometric coefficients of the three variables in the female sample (body weight, sitting height, and chest girth) sharply decreased in value from age 12 to 14 years. This result is unlikely to be due to differences in the correlation coefficients. It was also found, by comparing the allometric coefficient tables, that there were great differences between coefficients calculated with, and without, stature selection. The former often showed a markedly larger value than the latter, though this was not discussed by the author.

It is apparent that the allometric coefficient k is not a constant but a function of age. This has been implied by the results of Marshall (1980) and Hattori (1975), though they did not state it directly. The results of their studies suggest that in reality the equation should be:

$$y = ax^{k(t)}$$

where t is time, or age. However, this equation is difficult to analyse so that k has to be dealt with step by step. A similar investigation was also undertaken by Vajda *et al* (1980), based on a longitudinal growth data set composing 20 girls and 35 boys from Belgium, aged from 6 to 13 years. A datum point interpolation treatment was employed before the data processing.

2 METHODS

2.1 DESIGN OF THE EXPERIMENTS

2.1.1 Methods to determine volume distributions of limbs

The biomechanical characteristics investigated in this study have been calculated from the volume distribution of the concerned limb. The segment-zone method was employed to obtain distribution data for the centre of gravity, the principal moment of inertia, the radius of gyration and the volume of the body segment.

The segment zone method can be applied if the volume (or mass) distribution function of an object is unavailable.

Following a geometric model in which a series of discrete even distributions represents a continuous distribution at an interval, the segment zone method divides the body segment into a few 'segment zones'. All the body segments have continuous volume distributions. However, if there are a large number of divided zones, the length of each zone becomes small, with the result that the densities of the volume distribution at either end of each zone are nearly equal; the distribution in each zone can then be considered even. A series of even distributions can be used to imitate the real, but unknown, continuous distribution.

Suppose that a body has a mass distribution as shown in Figure 1.1, its length along the axis X being divided into n segments with their cross-sections perpendicular to axis X, and length of X_i (i=1,2,......,n-1,n; X_i are not necessarily equal to each other). The length of each piece X_i can be measured easily. In calculating the centre of gravity and the principal moment of inertia, the density of the mass distribution of the body segment must be given. Mathematically the density of distribution in an interval $[X_{i-1}, X_i)$, is the ratio of $m/(X_i-X_{i-1})$. So then it is essential that the value of m (mass in part of a limb segment with length X_i-X_{i-1}) is known. It is relatively easy to weigh the mass of dissected parts of the human body, but it is impractical to dissect and weigh a living subject. No direct method of achieving this objective is available.

2.1.1.1 *Basic assumptions of segment zone method*

When measuring the centre of gravity of body segments on living subjects, Bernstein *et al* (1931) made the assumption that the centre of gravity and the volume centre of the human body segment are the same, ie. the specific gravity of different parts of each limb are identical. This assumption has been adopted by other researchers in this field, though the results of some investigations (Dempster, 1955a, Clauser *et al,* 1969) demonstrated that the specific gravity is greater for the more distal part of the limbs. However, according to Bernstein and his co-workers' work (1931) on frozen cadavers, the mass centre can, in practice, be considered to coincide with the volume centre. Furthermore, analyses based on geometric methods are impossible without this assumption. The assumption has been adopted in this thesis. It should be noted that a degree of systematic error is bound to be introduced into the results. For example, the calculated centre of gravity is likely to be slightly more proximal than its true position.

2.1.1.2 Technique

Based on the assumption stated in 2.1.1, the mass of each segment piece X_i, m_i, can be calculated from its volume V_i, obtained experimentally in different ways, either directly or indirectly. Two different techniques were selected for data collection on different limb segments by the author.

2.1.1.2.1 Water displacement method

A water displacement technique was adopted, taking up the idea of segment-zone method, to obtain the volume distributions of the hand, forearm, upper arm, and calf. When a limb is placed in a container filled with water, an amount of water is displaced, with volume equal to that of the immersed part of the limb. By gradually immersing the limb further, a series of volume readings (V_i) will be obtained which represent the distribution of the immersed limb.

2.1.1.2.2 Elliptical zone modelling technique

For some body segments such as, for example, the thigh, the water displacement technique cannot be applied, due to practical difficulties in the measurement technique. An alternative method, elliptical zone modelling technique, was used in this situation to estimate V_i. Suppose that the body limb segment to be examined is composed of a series of oval cross-sections with different maximum and minimum axes. If the distance between each of two cross-sections and the two axes of each oval cross-section are known, the volume of each sub-segment, V_i, can be calculated.

2.1.1.3 Definition of the boundaries of the limb

The exact definition of the limb segments in human body inertial property studies has varied from author to author. Most researchers have defined the boundary of two segments as a plane going through the average rotation centre ('average' is used in this instance because a rotation centre is not fixed during the rotation). This definition is mechanical rather than anatomical, since it reflects the inertial properties of the limb correctly in terms of dynamics, but not with regard to the intact anatomical nature of the segments.

The present study has not adopted this definition for two reasons. Firstly, the study has also considered the effect of growth and development on the limbs. The definition quoted above is therefore not the most logical one for this purpose. Secondly, the definition is only suitable for studies using cadaveric specimens which can be dismembered (Dempster, 1955a; Chandler *et al,* 1975). However, in studies of living subjects, the boundary between two segments is identified by palpation, and in addition, as the water displacement method is used, the plane separating two limb segments should be perpendicular to the main axis of the limb in order that the boundary plane remains parallel to the water surface plane.

For the purpose of this study, the boundaries of a limb have been defined as:

a) Boundaries of the hand: The two planes perpendicular to the main axis of the hand, one of which is tangential to the tip of the third digit, the other pass through the wrist point, which is located at the middle of the line linking the styloid process of the ulna with that of the radius.

b) Boundaries of the forearm: The two planes perpendicular to the main axis of the forearm, the first passes through the wrist point (as described in section a), and the second passes through the gap between the head of the radius and the capitulum of the humerus.

c) Boundaries of the upper arm: Two planes perpendicular to the main axis of the upper arm, one of which is between head of radius and the capitulum of the humerus; the other is between the head of humerus and the acromion process of the scapular.

d) Boundaries of the calf: Two planes perpendicular to the main axis of the lower limb, one of which passes through the most protruding point of the medial malleolus, and the other passes through the gap between the medial condyle of the femur and tibia.

e) Boundaries of the thigh: these comprise two planes perpendicular to the main axis of the thigh. One passes through the gap between the medial condyles of the femur and tibia, and the other is at the height of the junction of both thighs on their medial aspect. This boundary differs from that as defined in other publications. It is more usually defined as the height of the centre of the head of femur (Dempster, 1955a; Contini *et al* 1962). However a similar boundary was used by Mech (1895).

2.1.2 Measurement of the centre of gravity of whole body

Equipment classified as a second class lever by Drillis and Contini (1966) was used in this research. The equipment is shown in Figure 2.1. It consists of a board, one end of which is fixed by an axle supported on two ball bearings. The subject lies the board (Figure 2.1) and the supine length is measured. The force F exerted downwards at the point T was weighed by an electronic digital scale with 0.1 kg minimum reading. The distance from the sole to the centre of gravity of the whole body C is then $C=C'+l$. The position of the centre of gravity is calculated as:

$$C'W=(F-F')(L-l)$$

$$C=(F-F')(L-l)/W+l$$

F′ is the force downwards at T when the board is empty, W is the body weight. C has three significant digits.

2.1.3 Anthropometry and somatotyping

The anthropometric measurements selected for this research are based on those defined by Martin (1957) and the IBP Handbook (Weiner and Lourie, 1969). In order to compare the data with those of Dangerfield (Personal communication), a few modifications were made in the techniques for the measurement of the limb length.

Somatotyping was undertaken using the Heath-Carter method (Carter, 1975), which is based on the anthropometric data with regression equations.

The measurements were undertaken on both the left and right sides of the body. The right limb was selected for the final data processing. There are two reasons for this. Firstly, it was realised that for the majority of the subjects it was easier to use the right limb in the water displacement procedure. Secondly, it has been reported that the difference between two body sides are very small (Laubach and McConville, 1967). Conventional anthropometric techniques and equipment are considered unlikely to detect such differences.

The details of anthropometric techniques are shown in Table 2.1.

2.1.4 Reproducibility

Reproducibility of the biomechanical variables was estimated by a pilot investigation to evaluate the reliability of the water displacement method and additionally to provide the parameters used to determine the sample size. During the main investigation, a small number of the subjects were selected at random in order that the reproducibility of technique could be obtained by repeated measurement.

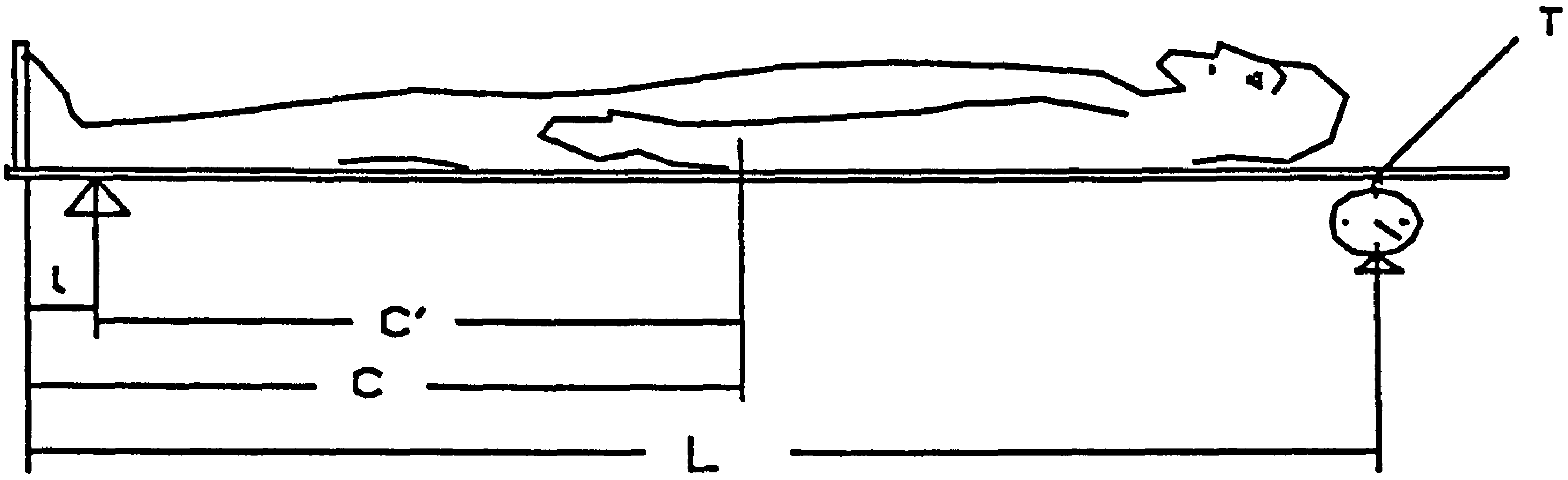


Fig. 2.1 Equipment for measuring the centre of gravity of the whole body

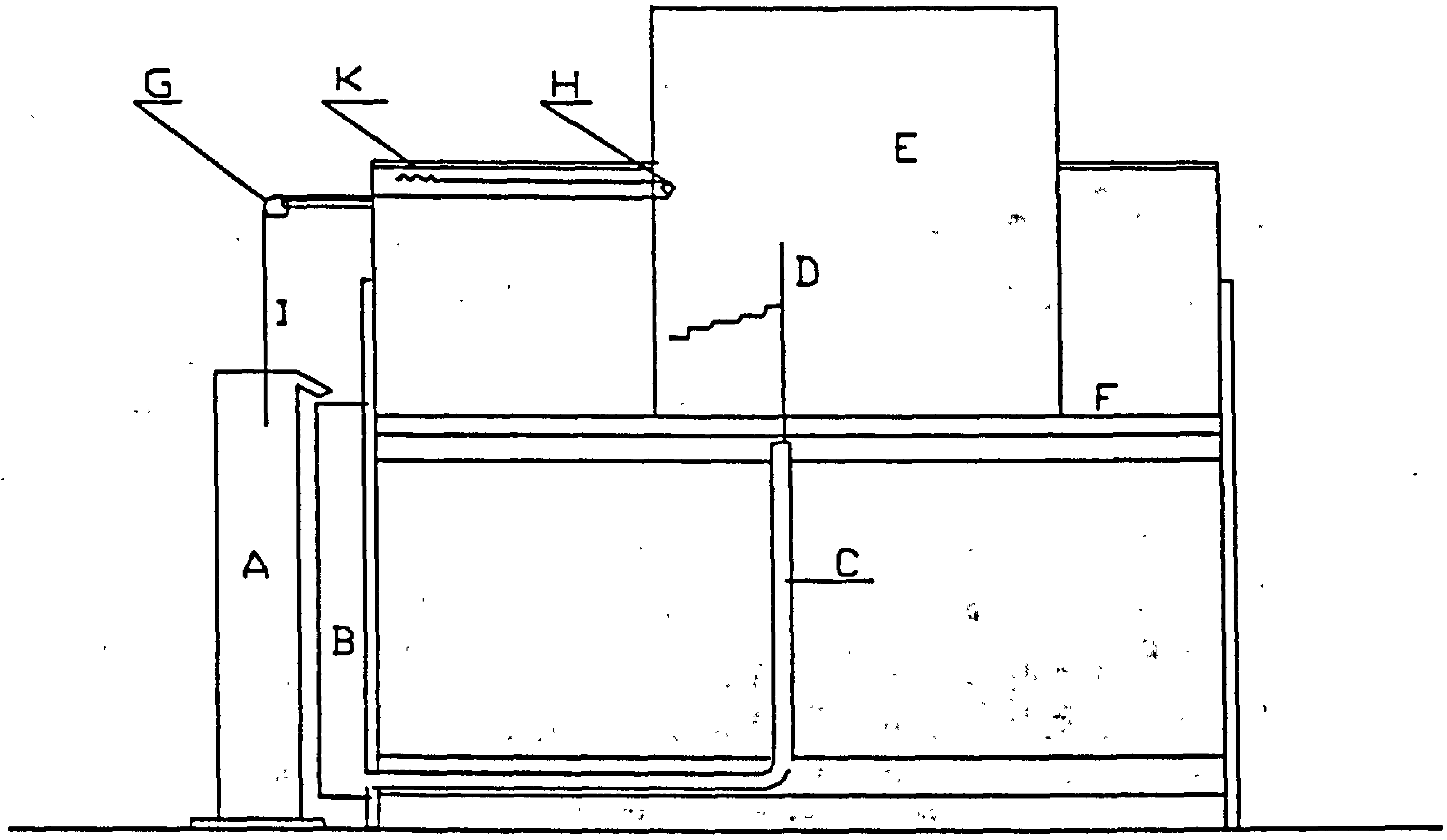


Fig. 2.2 Equipment for obtaining volume distribution data by the water displacement method

Table 2.1 Technique of anthropometry

Martin No.	Measurement	Definition	Instrument	Remarks
01	Stature	Standing surface to head top	Stadiometer	Head positioned by eye-ear plane
23	Sitting height	Sitting surface to head top	Stadiometer	
35	Shoulder breadth	Bi-acromial distance	Anthropometer	
40	Hip Breadth	Biiliac distance	Anthropometer	
	Skinfold, Triceps	Vertical skinfold at triceps	Harpenden-skinfold-caliper	
	Skinfold, Subscapular	45 ° from horizontal		
	Skinfold, Supraspinale	45 ° from horizontal		
	Skinfold, Calf	--		
	Bicond. dia. humerus	Medial-lateral epicondylar	Vernier calliper	
	Bicond. dia. femur	Medial-lateral epicondylar	Vernier calliper	
65**	Upper arm girth, Maximum	Maximum girth of upper arm	Tape	
66	Forearm girth, P	Maximum girth of forearm	Tape	
67	Wrist girth	minimum girth at wrist	Tape	
68	Thigh girth	Maximum girth of thigh	Tape	
	Thigh girth, D	Girth above knee bone	Tape	
69	Calf girth	Maximum girth of calf	Tape	
	Ankle girth	Minimum girth at ankle	Tape	
47*	Upper arm length	Acromion to Radiale	Tape	
56*	Tibia length	Tibiale to Sphyrion	Anthropometer	
58	Foot length	Akropodion to Pternion	Anthropometer	
59	Foot breadth	mt. tibiale to mt. fibulare	Anthropometer	
45*	Upper limb length	Acromion to Dactylion	Tape	
49	Hand length	Stylion to Dactylion	Anthropometer	
36	Chest breadth	At mesosternale level	Anthropometer	

* The method or instrument is different from that recommended by Martin. ** The definition is different from that of Martin

The results reveals that the upper arm measurement had the greatest magnitude of error attributed to methodology, and the centre of gravity had the worst reproducibility. In the estimation of the mass centre of the upper arm, the error of the method was found to be almost the same magnitude as the population standard deviation, even though its value was only 1.5% (the population SD was also small).

Method error of the measurement of the CG and RG, the correlation coefficient for the test-retest value of the PMI and volume, are listed in Table 2.2. The method error (δ_e) is defined as:

$$\delta_e = \sqrt{\frac{1}{2n}\sum_{i=1}^{n} d_i}$$

where d is the difference between the two measurements. δ_e has the same unit as the variable which it describes. For the CG and RG, it is expressed as the percentage of the limb length. Due to the large variation in the PMI and the volume, their reproducibility is shown as a correlation coefficient, similar to that of Stijnen *et al* (1983).

TABLE 2.2 Reproducibility

	Hand^1	*FA*^{2}	*UA*^{2}	*FA-Hand*	*UA-FA*^{2}	*UL*^{1}
CG*	1.13	1.34	1.66	0.86	1.21	0.94
RG*	0.49	0.48	0.66	0.21	0.45	0.32
PMI**	0.98	0.89	0.95	0.98	0.95	0.99
Volume**	0.99	0.95	0.97	-	-	0.99

* Technical error; ** Correlation coefficient of test-retest values
FA: Forearm; UA: Upper arm; UL: Upper limb
1) No.=7; 2) No.=16

2.2 DATA COLLECTION

2.2.1 Sample

The data collection was undertaken in three Liverpool schools. These were the Blessed Sacrament Junior School, Archbishop Beck Lower School and Fazakerley Comprehensive School.

The schools selected enabled a full sample of children of different ages to be measured. A letter was sent by the school to the parents of the child in classes selected at random requesting permission to take the measurements. All responses from the parents were positive except for two children. In view of the size of the sample, these two cases were not considered to affect the validity of the sample.

The sex, date of birth, date of measurement, and racial type of each subject was recorded. Anthropometric and body segment mass distribution measurements were taken separately. Volume distribution data from any subjects unable to maintain a steady posture during the water displacement procedure were excluded from the data set.

Two non-Caucasian subjects were also excluded from the final data processing to ensure the sample was of a consistent genetic background.

2.2.2 Techniques

2.2.2.1 Mass distribution of body segments

All of these data were collected by the author.

2.2.2.1.1 Water displacement method

The volume distribution of the hand, forearm, upper arm and the calf were measured using the water displacement method. The equipment was specially designed for this purpose. The principle of this method is the same as that of Drillis *et al* (1966).

The equipment (Figure 2.2) employs two cylinders (A and B). Cylinder A is used for the water supply and cylinder B receives and permits measurement of the water volume. A narrow tube (C) is linked with cylinder B at its base so that the water surfaces in B and C are at the same level; a pen (D) is mounted on a float in the tube C. A board (E), marked with a series of coordinates, moves horizontally along the slideway (F). A pulley block system, having a fixed pulley (G) and a movable pulley (H), is linked with a piece of string (I) and spring (K).

As shown in Figure 2.2, the fixed pulley G is above the cylinder A. When a subject immerses his limb in the cylinder to a depth L, the string I, which is fixed around the distal end of the subject's limb will pull the board E a distance of L/2. At the same time, a quantity of water equal to the volume of the submersed limb segment with length L will be displaced into cylinder B, so that the water surface in B and C will rise. This results in pen D rising. A curve will be drawn on the board E when it moves horizontally and the pen moves perpendicularly. The shape of the curve depends on the amount of the water displaced when the limb moves in the cylinder A downwards through the whole distance.

The cross-section of the hand is relatively small. The apparatus described above can therefore not record its volume accurately; an alternative method has been devised to overcome this. A small plexiglass box was constructed and a small lip was fixed to its upper margin. Before undertaking measurements, scale marks were made on the subject's hand which denoted the length from the distal end of the hand (tip of the third finger). The water displaced by each hand segment successively passed over the lip, was collected in a small volumetric cylinder (50 ml) and then measured. By lowering the hand into the box one mark after another, a series of readings, which represent the density of the mass distribution, was obtained.

2.2.2.1.2 Elliptical zone modelling technique

This method was used only for the mass distribution measurement of the thigh. The subject was asked to stand erect with both legs slightly separated. Three measurements were taken for each cross-section. These were: the height (H), the maximum length of the cross-section in sagittal direction (2a) and the maximum length in coronal direction (2b). The values of a and b were used to calculate the area of the cross-section which was assumed to be an ellipse. The area of an ellipse is

$$A = 3.1416 \times a \times b$$

The volume of the segment piece between two cross-section was estimated as

$$V = \frac{1}{3} h(A_1^2 + A_2^2 + \sqrt{A_1 A_2})$$

where A_1 and A_2 are the areas of the ends of the segment piece, h is the distance between the two ends.

By repeating this procedure, the volume distribution of the thigh can be determined.

2.2.2.2 *Anthropometry*

The majority of these data were collected by the author. However, a small number of the subjects (mainly distributed at the lower end of the age range) were measured by Dr. Dangerfield. The techniques used to take the anthropometric measurements had been agreed and unified between the two workers before the investigation began.

2.3 DATA PREPROCESSING

2.3.1 Data input and preprocessing

2.3.1.1 Volume distribution data

The data collected in the field measurements with the water displacement method were recorded in two paired columns. One consisted of a series of figures representing lengths of the main axis of the limb, while the other column contained the accumulated volume data of the same section of the limb.

A program in FORTRAN 77 (Appendix I) was written by the author to calculate the values for the centre of gravity, principal moment of inertia, and radius of gyration. There were two stages in the program. Stage one of the program converted the volume distribution data into that of mass distribution, using Dempster's (1955a) data for the specific gravity of each limb segment; this procedure did not make any difference for the calculation of the centre of gravity and radius of gyration of each individual segment. However, it did improve the calculation of the results for the three inertial properties of the multi-segment unit (for example, the forearm with hand or the upper limb), and that for the principal moment of inertia of individual segments. Stage two employed a subroutine to calculate each inertial characteristic. The algorithms were defined from the direct definition of the characteristics, which have been described in Chapter one.

The volume distribution measurements of the thigh could not be obtained directly, as described earlier. The data collected in field measurements correspond to the maximum and minimum axes of each section plane and its distance to an original predetermined plane (which was the most distal one). The volume of the section can then be defined as the volume of a geometric object shaped like an elliptical conical section, but with different ellipticities for the two ends of the section. All other cross-sections in this section are ellipses having changing ellipticities proportionally along the axis of the section. This volume can be estimated by using a truncate cone having a height the same as that of the conical section, and with cross-sectional areas of the two ends the same as that of the represented object.

A FORTRAN 77 program was written by the author to transfer the original data for the thigh to the volume distribution data. The following calculations for the inertial characteristics for the thigh are the same as those of the calf.

2.3.1.1.1 Calculation of centre of gravity

The centre of gravity of each limb segment was calculated directly using the definition and formula stated earlier (See section 1.2.1).

2.3.1.1.2 Calculation of principal moment of inertia

Unlike the centre of gravity, the principal moment of inertia cannot be determined by solely using the mass data and position of each segment division. It is also dependent on the shape of these divisions. Because this shape information was unavailable, and because the values for the two principal moments of inertia I_{xx} and I_{yy} are nearly equal (Jensen, 1978; Ackland, *et al,* 1988; Ackland, 1990, personal communication). The data for the thigh in this study also showed that the two axes (depth and width of thigh) are very similar to each other. It is necessary, and reasonable, for the purpose of this thesis, to assume this shape was circular. This allowed the computation of the value of principal moment of inertia using the formula described in section 1.2.2. The results for the calculated principal moment of inertia, 'I', would lie between the range of I_{xx} and I_{yy}. If $I_{xx} \approx I_{yy}$, 'I' gives good estimation to them.

2.3.1.2 Anthropometric data

The raw anthropometric data were recorded on a proforma. In addition, each subject was allocated an observation number, and personal records such as sex, date of birth were recorded. The date of survey was also recorded. These data were processed to yield a data set which comprised the observation number, decimal age, sex, direct and derived anthropometric variables and indices, values for somatotype and location of the centre of gravity of the whole body. The somatotype was calculated from the anthropometric data using Heath-Carter's formula (Carter, 1975).

All missing data were given a value less than, or equal to, zero in order that they could be excluded in subsequent computer processing.

2.3.1.3 Merging of the data offsets

The anthropometric data were then contained in an unformatted FORTRAN data file with the data relating to inertial characteristics of the upper limb, calf, and thigh, using the same observation numbers to identify the same individual.

2.3.2 Error detection in the data file

2.3.2.1 Volume distribution data

The volume distribution data of a limb segment consists of a paired series, one which is of distance, the other is volume. Both of them are monotonically increasing, eg. if x_i and x_j are any two numbers in either of the two series, and if $j > i$, then, $x_j > x_i$.

Based on this property of the data, a programme was written to check the data in the two series. If a non-increasing datum is found, the observation number, and the position of the datum in the series are printed so that the error can be traced.

2.3.2.2 Anthropometric data

The anthropometric data were typed into computer memory in a fixed format (most mistakes can be found using this technique), and each record (corresponding to one observation) was scanned through after data entry. However, because of the large data set, errors are unavoidable in prolonged typing. In fact, the sources of error were at the very beginning of the data collection. During the field measurements, from the reading and reporting, of the anthropometrist to the listening and writing of data on the proforma by the clerk, mistakes might occur at any stage. It is therefore essential to check the data very carefully.

A program was written to detect the obvious errors in the data set. The programme prints out five of the biggest and five the smallest values of each variable with their record numbers, so that these values can be checked and analysed in detail. Most of the serious errors have been found and corrected by this way.

However, this method can only detect the extreme values of each variable. If a mistake occurs in a value falling within the normal range, it cannot be detected this way. For example, one cannot tell if a forearm datum has a wrong length value of 220 mm, but it can be easily proved that this forearm is unlikely to belong to a subject with stature of 1750 mm. Based on this premise, such relationships are considered to be suitable for detecting the datum error. The logged values of each variable were plotted, against the logged cubic root of the body weight, on a X-Y coordinate. The datum points usually form a 'belt'. Any observation falling off this belt was carefully checked, and corrected, if necessary.

After all the data preprocessing, a 'checked' data set was established for further processing and analysing.

2.4 MECHANICAL PARAMETERS OF A TRUNCATED CONE

A truncated cone, as shown in Figure 1.2, with r_1 and r_2 being the radii of its two ends, has the mechanical parameters:

$$CG = \frac{\pi\int_0^1 (r_1 + zr_2 - zr_1)^2 z dz}{\pi\int_0^1 (r_1 + zr_2 - zr_1)^2 dz} = \frac{3s^2 + 2s + 1}{4(s^2 + s + 1)}$$

$$CG^2 + RG^2 = \frac{PMI}{M} = \frac{3r_1^2(s^4 + s^3 + s^2 + s + 1) + 2(6s^2 + 3s + 1)}{20(s^2 + s + 1)}$$

solving these simultaneous equations, we have:

$$r_1^2 = \frac{(20s^2 + s + 1)(CG^2 + RG^2) - 2(6s^2 + 3s + 1)}{3(s^4 + s^3 + s^2 + s + 1)} \qquad (1)$$

$$s = \frac{1 - 2CG \pm \sqrt{2(-1 + 6CG - 6CG^2)}}{4CG - 3} \qquad (2)$$

In these equations, $s=r_2/r_1$. This mechanical procedure is going to be used to model the human limb segments.

3 STATISTICAL ANALYSIS OF THE DATA: RESULTS

The major objectives of this research were to determine the inertial characteristics of human body limb segments, investigate their individual properties, and to determine the extent of correlations among the limb segments themselves and with conventional anthropometric variables. These would yield information about the size and shape changes of children during growth. The selection of the subjects in different age groups was such as to allow for ontogenetic changed to be observed, as well as maximising the variability of each variables. This would permit correlation and regression analysis to be carried out.

3.1 SAMPLE PARAMETERS

Basic statistical parameters, including the mean, standard deviation (SD), coefficient of variation (CV), standard error (SE) for each age-sex group, and the 'F' values for the analysis of variance for each sex grouped by age are listed in Table 3.2.3 to 3.2.74. The units are millimetres (mm) for linear measurement except for skinfolds, which is in tenths of millimetres; kilogrammes (kg) for body weight, millilitre (ml) for volume, and cm^2kg for principal moment inertia. The centre of gravity of a limb segment is expressed as a ratio between the distance from centre of gravity to the distal end of the limb segment, and the length of that limb. The centre of gravity of the whole body is expressed as the ratio of its height above the standing surface to whole body stature. The radius of gyration of a limb is expressed as the ratio between its length and the limb length. The names of the variables corresponding to the variable sequence numbers are listed in Table 3.1, and the dimensions used for the variables and descriptions of the parameters are listed in Tables 3.2.1 and 3.2.2.

3.1.1 Significance test of the mean difference between sexes

The Student's 't' test was used to test the significance of the difference between the sex means. To undertake this test, the mean, variation and the sample size of the two sexes are required. In this work, the corrected mean by interpolation of each standard age point, the standard deviation and the sample number of the corresponding real age group sample were employed to calculate the 't' values. For example, at age 9, the estimated mean stature is 1326.2 mm and 1320.1 mm for boys and girls respectively, the respective standard deviations, 45.6 mm at 9.0 years for boys and 61.5mm at 9.1 for girls, were used. The results of the tests are shown in Table 3.3 and Table 3.4. Table 3.4 is composed of columns which correspond to a variable and a standard age point. The results expressed by one, two, or three arrows represent significance levels of $p < 0.2$, $p < 0.1$, or $p < 0.05$. The upwards direction of an arrow indicates that the male mean is larger; a downward direction indicates that the female mean is larger.

3.1.1.1 Somatotype

Endomorphy is determined by the sum of the skinfold thicknesses at triceps, subscapular, and supraspinale. This reflects the overall fatness of the subjects. As shown in Tables 3.3 and 3.4, in all six age groups from age eight to age thirteen which are comparable, girls have a higher value for this variable than boys. Only at age 13, is the difference significant at $p < 0.05$ level, but the same trend can be observed for age group 9, and 10, at $p < 0.10$. Girls therefore have an average higher value of endomorphy than boys from age 8 to age 13.

The results indicate that, even at very young ages, there are sexual differences in body build between males and females. Pre-adolescent girls, on average, have more fat deposited under their skin than boys. However, Ectomorphy suggests that boys are more linear. Table 3.3 indicates that this trend becomes more marked at adolescence. Mesomorphy which reflects musculoskeletal robustness, has similar values for the sexes at each age group. However, the boys have a higher mean value throughout the age range.

TABLE 3.1 Variable List

No.	Variable	No.	Variable
1	Observation No.	39	CG* of whole body
2	Sex	40	CG, Hand
3	Age	41	CG, Forearm
4	Endomorphy	42	CG, Upper arm
5	Mesomorphy	43	CG, Forearm with hand
6	Ectomorphy	44	CG, Upper arm with forearm
7	Weight	45	CG, Upper limb
8	Stature	46	CG, Calf
9	Sitting height	47	CG, Thigh
10	Skinfold, Triceps	48	PMI**, Hand
11	Skinfold, Subscapular	49	PMI, Forearm
12	Skinfold, Suprailiac	50	PMI, Upper arm
13	Skinfold, Calf	51	PMI, Forearm with hand
14	Bicondylar diameter, Humerus	52	PMI, Upper arm with forearm
15	Bicondylar diameter, Femur	53	PMI, Upper limb
16	Girth, Upper arm, Maximum	54	PMI, Calf
17	Girth, Forearm, Proximal	55	PMI, Thigh
18	Girth, Wrist	56	RG***, Hand
19	Girth, Thigh, Proximal	57	RG, Forearm
20	Girth, Thigh, Distal	58	RG, Upper arm
21	Girth, Calf, Maximum	59	RG, Forearm with hand
22	Girth, Ankle	60	RG, Upper arm with forearm
23	Length, Total upper limb	61	RG, Upper limb
24	Length, Forearm	62	RG, Calf
25	Length, Forearm with hand	63	RG, Thigh
26	Length, Upper arm	64	Volume, Hand
27	Length, Hand	65	Volume, Forearm
28	Length, Thigh	66	Volume, Upper arm
29	Length, Tibia	67	Volume, Upper limb
30	Length, Foot	68	Volume, Calf
31	Length, Total lower limb	69	Volume, Thigh
32	Breadth, Shoulder	70	Ratio****, Hand volume
33	Breadth, Hip	71	Ratio, Forearm volume
34	Breadth, Hand	72	Ratio, Upper arm volume
35	Breadth, Foot	73	Ratio, Upper limb volume
36	Breadth, Chest	74	Ratio, Calf volume
37	Index, Hip/Shoulder breadth		
38	Index, Sitting height/stature		

*CG: Centre of gravity: **PMI: Principal moment of inertia

***RG: Radius of Gyration: ****Ratio: Ratio of the specified variables with Body weight

TABLE 3.2.1 Dimension of the variables

Variables	Sequence No.	Dimension
Age	3	Years
Somatotype	4-6	None
Weight	7	Kilogram (kg)
Stature	8	Millimeter (mm)
Sitting height	9	Millimeter (mm)
Skinfold thickness	10-13	Decimillimeter (dmm)
Bicondylar diameter	14-15	Millimeter (mm)
Girth	17-22	Millimeter (mm)
Length	23-31	Millimeter (mm)
Breadth	32-36	Millimeter (mm)
Index	37-38	None
CG	39-47	None
PMI	48-55	cm^2kg
RG	56-63	None
Volume	64-69	Milliliter (ml)
Volume ratio	70-74	None

TABLE 3.2.2 Description of the parameters

Parameter	Description
Mean	Sample Mean
SD	Standard deviation
CV	Coefficient of variation
SE	Standard Error
F	Quotient of inter- /intra- age group variances in the analysis of variance grouped by age

TABLE 3.2.3 Age (Years)

	MALES					FEMALES				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	8.4	0.1	1.7	0.0	13	8.4	0.1	0.9	0.0
9	32	9.0	0.3	3.2	0.1	35	9.1	0.3	3.3	0.0
10	30	9.9	0.3	2.6	0.0	29	9.9	0.3	3.1	0.1
11	19	11.0	0.3	3.0	0.1	15	11.1	0.3	3.1	0.1
12	16	12.0	0.3	2.5	0.1	16	12.1	0.3	2.4	0.1
13	28	13.0	0.3	2.0	0.0	17	13.1	0.3	2.0	0.1
14	21	14.0	0.3	1.9	0.1	11	13.9	0.4	2.6	0.1
15	23	15.1	0.3	1.8	0.1	12	15.0	0.2	1.2	0.1
16	13	15.9	0.2	1.3	0.1	5	15.6	0.0	0.3	0.0

TABLE 3.2.4 Endomorphy

	MALES (F= 0.6)					FEMALES (F=1.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	2.1	0.6	28.7	0.20	13	2.6	0.8	31.5	0.2
9	32	2.6	0.9	34.2	0.20	35	3.0	1.2	41.2	0.2
10	30	2.7	1.4	50.3	0.20	29	3.2	0.9	28.3	0.2
11	19	3.1	1.9	60.4	0.40	15	3.5	1.5	42.6	0.4
12	16	2.9	1.6	55.0	0.40	16	3.2	1.1	34.9	0.3
13	28	2.8	1.1	39.9	0.20	14	3.7	1.3	35.4	0.4
14	21	2.6	1.3	49.9	0.30	4	3.5	1.2	35.2	0.6
15	23	2.5	1.5	59.0	0.30	-	-	-	-	-
16	13	2.6	0.9	34.6	0.20	-	-	-	-	-

TABLE 3.2.5 Mesomorphy

	MALES (F= 10)					FEMALES (F=0.5)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	4.2	1.2	28.6	0.4	13	4.0	0.8	20.0	0.2
9	32	4.5	0.8	17.1	0.1	35	4.0	1.0	24.6	0.2
10	30	4.3	0.8	18.2	0.1	29	4.2	0.9	20.5	0.2
11	19	4.6	1.2	25.5	0.3	15	4.2	0.9	20.0	0.2
12	16	4.2	1.1	25.7	0.3	16	4.3	1.2	27.6	0.3
13	28	4.5	1.2	26.3	0.2	14	4.5	0.9	19.4	0.2
14	21	4.1	1.4	34.6	0.3	4	4.2	0.9	20.8	0.4
15	23	4.0	1.0	25.5	0.2	-	-	-	-	-
16	13	3.9	0.9	23.7	0.3	-	-	-	-	-

TABLE 3.2.6 Ectomorphy

	MALES (F= 1.7)					FEMALES (F= 2.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	4.5	2.1	46.2	0.7	13	4.1	2.1	50.5	0.6
9	32	3.6	1.3	36.0	0.2	35	3.8	1.7	44.0	0.3
10	30	3.3	1.1	34.4	0.2	29	2.8	1.1	40.0	0.2
11	19	2.9	1.4	47.1	0.3	14	2.8	1.2	43.5	0.3
12	16	3.6	1.4	39.7	0.4	16	3.1	1.6	53.2	0.4
13	27	3.4	1.2	34.4	0.2	17	2.2	1.2	54.7	0.3
14	21	4.0	1.2	30.5	0.3	11	2.9	1.7	58.8	0.5
15	23	3.7	1.4	36.4	0.3	12	2.9	1.2	41.0	0.3
16	13	3.6	1.1	29.8	0.3	5	2.2	1.7	75.8	0.70

TABLE 3.2.7 Weight (kg)

	MALES (F= 38.6)					FEMALES (F= 33.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	24.31	4.38	18.0	1.46	13	23.49	4.27	18.2	1.18
9	32	27.73	4.02	14.5	0.71	35	27.65	5.38	19.5	0.91
10	30	31.72	6.09	19.2	1.11	29	32.93	6.29	19.1	1.17
11	19	38.03	10.50	27.6	2.41	14	37.97	6.09	16.0	1.63
12	16	40.54	8.88	21.9	2.22	16	40.06	10.14	25.3	2.54
13	27	44.14	7.82	17.7	1.50	17	50.52	7.39	14.6	1.79
14	21	47.67	9.09	19.1	1.98	11	50.33	13.80	27.4	4.16
15	23	54.09	11.38	21.0	2.37	12	51.72	9.36	18.1	2.70
16	13	60.16	9.82	16.3	2.72	5	58.88	11.11	18.9	4.97

TABLE 3.2.8 Stature (mm)

	MALES (F= 81.0)					FEMALES (F= 62.4)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	1300.8	60.5	4.7	20.2	13	1270.4	35.6	2.8	9.9
9	32	1325.4	45.6	3.4	8.1	35	1327.1	61.5	4.6	10.4
10	30	1371.8	58.8	4.3	10.7	29	1364.6	62.3	4.6	11.6
11	19	1428.2	83.1	5.8	19.1	15	1440.5	53.4	3.7	13.8
12	16	1497.6	67.7	4.5	16.9	16	1463.0	68.0	4.6	17.0
13	28	1530.1	86.1	5.6	16.3	17	1546.4	60.8	3.9	14.7
14	21	1605.5	90.1	5.6	19.7	11	1566.5	70.9	4.5	21.4
15	23	1657.3	70.7	4.3	14.7	12	1591.8	59.3	3.7	17.1
16	13	1717.6	77.2	4.5	21.4	5	1619.0	21.9	1.4	9.8

TABLE 3.2.9 Sitting height (mm)

	MALES (F= 44.4)					FEMALES (F= 52.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	702.8	42.6	6.1	14.2	13	681.5	13.2	1.9	3.7
9	31	703.5	38.0	5.4	6.8	34	703.8	34.8	4.9	6.0
10	30	729.3	31.3	4.3	5.7	29	726.9	35.2	4.8	6.5
11	19	753.8	38.5	5.1	8.8	15	760.1	32.6	4.3	8.4
12	15	784.7	34.3	4.4	8.8	16	767.0	40.7	5.3	10.2
13	27	791.9	44.3	5.6	8.5	17	830.4	33.3	4.0	8.1
14	21	815.6	51.5	6.3	11.2	11	830.5	46.1	5.5	13.9
15	23	853.3	48.4	5.7	10.1	12	848.8	39.3	4.6	11.4
16	13	885.8	48.4	5.5	13.4	5	866.6	36.3	4.2	16.2

TABLE 3.2.10 Skinfold, Triceps (dmm)

	MALES (F= 1.2)					FEMALES (F= 1.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	103.6	33.8	32.7	11.3	13	116.6	25.7	22.0	7.1
9	32	116.9	33.0	28.2	5.8	35	132.9	49.1	36.9	8.3
10	30	112.7	43.6	38.7	8.0	29	144.2	39.9	27.7	7.4
11	19	133.7	64.7	48.4	14.8	15	140.4	50.6	36.1	13.1
12	16	121.9	61.8	50.7	15.5	16	133.8	38.3	28.6	9.6
13	28	113.6	41.4	36.4	7.8	14	157.1	60.8	38.7	16.3
14	21	103.5	46.9	45.3	10.2	4	152.0	51.5	33.9	25.7
15	23	99.3	49.4	49.7	10.3	-	-	-	-	-
16	13	97.7	21.9	22.4	6.1	-	-	-	-	-

TABLE 3.2.11 Skinfold, Subscapular (dmm)

	MALES (F= 1.2)					FEMALES (F= 2.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	58.2	13.9	23.8	4.6	13	67.6	30.8	45.5	8.5
9	32	66.8	24.8	37.1	4.4	35	75.9	28.9	38.1	4.9
10	30	69.4	37.9	54.6	6.9	29	86.5	35.0	40.5	6.5
11	19	99.4	83.1	83.6	19.1	15	107.0	62.6	58.5	16.2
12	16	86.1	67.5	78.4	16.9	16	85.6	37.8	44.1	9.4
13	28	82.6	36.6	44.2	6.9	14	111.9	51.1	45.6	13.6
14	21	80.9	35.5	43.9	7.7	4	100.0	42.2	42.2	21.1
15	23	83.4	54.5	65.3	11.4	-	-	-	-	-
16	13	81.7	22.0	26.9	6.1	-	-	-	-	-

TABLE 3.2.12 Skinfold, Suprailiac (dmm)

	MALES (F= 0.6)					EMALES (F= 1.1)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	57.6	16.5	28.6	5.5	13	74.8	29.6	39.6	8.2
9	32	74.5	34.5	46.3	6.1	35	90.2	47.1	52.2	8.0
10	30	93.0	58.2	62.6	10.6	29	87.5	32.8	37.5	6.1
11	19	94.2	68.2	72.4	15.7	15	102.9	53.6	52.0	13.8
12	16	88.1	58.3	66.1	14.6	16	102.3	44.1	43.1	11.0
13	28	85.3	44.2	51.9	8.4	14	103.5	35.8	34.6	9.6
14	21	83.9	52.1	62.1	11.4	4	90.0	28.1	31.3	14.1
15	23	81.4	63.5	78.0	13.2	-	-	-	-	-
16	13	80.9	48.7	60.1	13.5	-	-	-	-	-

TABLE 3.2.13 Skinfold, Calf (dmm)

	MALES (F= 1.4)					FEMALES (F= 2.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	72.4	15.4	21.2	5.1	13	96.9	21.9	22.6	6.1
9	32	91.8	28.1	30.6	5.0	35	112.1	41.3	36.9	7.0
10	30	92.1	35.2	38.3	6.4	29	132.3	53.9	40.7	10.0
11	19	124.2	80.7	65.0	18.5	15	135.3	45.0	33.3	11.6
12	16	116.1	70.7	60.9	17.7	16	109.1	41.0	37.6	10.3
13	28	108.9	39.2	36.0	7.4	14	136.1	74.3	54.6	19.9
14	21	102.0	52.4	51.4	11.4	4	145.8	65.8	45.1	32.9
15	23	99.7	71.2	71.4	14.8	-	-	-	-	-
16	13	93.7	28.7	30.6	8.0	-	-	-	-	-

TABLE 3.2.14 Bicondylar diameter, Humerus (mm)

	MALES (F= 28.1)					FEMALES (F= 16.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	52.4	3.4	6.5	1.1	13	50.2	2.2	4.3	0.6
9	32	54.5	3.0	5.4	0.5	35	52.9	3.7	7.0	0.6
10	30	56.1	3.8	6.8	0.7	29	53.5	3.1	5.8	0.6
11	19	56.9	4.5	7.9	1.0	15	56.9	3.9	6.9	1.0
12	16	60.4	3.7	6.1	0.9	16	58.1	3.8	6.5	0.9
13	28	62.0	4.5	7.2	0.8	14	60.4	2.4	4.0	0.6
14	21	64.7	6.8	10.5	1.5	4	60.0	4.8	7.9	2.4
15	23	65.0	4.1	6.3	0.9	-	-	-	-	-
16	13	67.6	2.5	3.7	0.7	-	-	-	-	-

TABLE 3.2.15 Bicondylar diameter, Femur (mm)

	MALES (F= 20.3)					FEMALES (F= 15.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	79.9	4.7	5.8	1.5	13	76.3	3.4	4.5	0.9
9	32	82.3	4.1	5.0	0.7	35	79.3	4.9	6.2	0.8
10	30	84.9	4.9	5.8	0.9	29	81.9	5.3	6.5	1.0
11	19	88.2	6.9	7.8	1.6	15	85.7	4.9	5.7	1.3
12	16	93.0	6.5	7.0	1.6	16	86.8	7.1	8.2	1.8
13	28	93.1	5.3	5.7	1.0	14	91.9	5.2	5.6	1.4
14	21	94.1	8.5	9.0	1.9	4	91.0	7.1	7.8	3.5
15	23	95.1	6.6	6.9	1.4	-	-	-	-	-
16	13	97.3	5.4	5.5	1.5	-	-	-	-	-

TABLE 3.2.16 Girth, Upper arm, Maximum (mm)

	MALES (F= 16.6)					FEMALES (F= 14.4)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	190.7	18.7	9.8	6.2	13	186.3	15.7	8.4	4.4
9	32	202.4	16.7	8.3	3.0	35	199.3	21.8	10.9	3.7
10	30	206.8	24.3	11.8	4.4	29	212.4	22.1	10.4	4.1
11	19	225.3	33.5	14.9	7.7	15	226.3	18.9	8.4	4.9
12	16	225.0	28.7	12.8	7.2	16	229.8	29.2	12.7	7.3
13	28	243.8	44.8	18.4	8.5	14	252.2	23.3	9.2	6.2
14	21	247.8	30.1	12.1	6.6	4	246.3	33.6	13.7	16.8
15	23	261.2	27.6	10.6	5.8	-	-	-	-	-
16	13	274.3	25.6	9.3	7.1	-	-	-	-	-

TABLE 3.2.17 Girth, Forearm, Proximal (mm)

	MALES (F= 23.5)					FEMALES (F= 15.8)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	186.6	12.8	6.9	4.3	13	179.2	9.9	5.5	2.7
9	31	193.2	10.3	5.3	1.9	35	191.1	14.9	7.8	2.5
10	30	198.9	15.4	7.7	2.8	28	198.2	14.8	7.5	2.8
11	19	208.5	22.0	10.5	5.0	15	208.5	15.3	7.3	3.9
12	10	203.8	9.8	4.8	3.1	16	210.1	16.5	7.9	4.1
13	17	223.2	17.6	7.9	4.3	14	225.9	12.9	5.7	3.4
14	15	223.7	15.1	6.8	3.9	4	220.8	26.0	11.8	13.0
15	16	236.6	21.5	9.1	5.4	-	-	-	-	-
16	11	244.6	14.3	5.8	4.3	-	-	-	-	-

TABLE 3.2.18 Girth, Wrist (mm)

	MALES (F= 26.1)					FEMALES (F= 18.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	126.9	11.0	8.7	3.7	13	125.0	4.9	3.9	1.4
9	32	131.8	6.1	4.6	1.1	35	129.5	8.1	6.2	1.4
10	30	135.6	9.3	6.9	1.7	29	133.8	9.5	7.1	1.8
11	19	141.7	12.3	8.7	2.8	15	144.9	13.7	9.5	3.5
12	16	145.6	7.7	5.3	1.9	16	142.6	8.8	6.1	2.2
13	28	145.6	11.3	7.8	2.1	14	152.1	8.1	5.3	2.2
14	21	153.1	10.5	6.9	2.3	4	142.8	11.3	7.9	5.6
15	23	157.6	13.2	8.4	2.8	-	-	-	-	-
16	13	164.5	7.4	4.5	2.1	-	-	-	-	-

TABLE 3.2.19 Girth, Thigh, Proximal (mm)

	MALES (F= 15.4)					FEMALES (F= 18.5)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	8	369.8	43.2	11.7	15.3	13	384.4	23.8	6.2	6.6
9	32	399.1	32.8	8.2	5.8	35	412.5	46.2	11.2	7.8
10	30	407.6	46.2	11.3	8.4	29	443.2	46.2	10.4	8.6
11	19	453.1	63.6	14.0	14.6	15	467.1	44.3	9.5	11.4
12	16	447.3	59.2	13.2	14.8	16	460.1	56.1	12.2	14.0
13	27	469.5	42.6	9.1	8.2	14	529.5	45.2	8.5	12.1
14	21	470.6	43.3	9.2	9.4	3	540.3	82.7	15.3	47.7
15	22	487.3	66.4	13.6	14.2	-	-	-	-	-
16	13	520.2	43.7	8.4	12.1	-	-	-	-	-

TABLE 3.2.20 Girth, Thigh, Distal (mm)

	MALES (F= 10.9)					FEMALES (F= 17.5)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	8	264.6	23.4	8.9	8.3	13	271.2	18.7	6.9	5.2
9	32	281.3	22.1	7.9	3.9	35	286.0	30.2	10.6	5.1
10	30	291.3	28.7	9.9	5.2	29	302.4	33.7	11.1	6.2
11	19	321.2	42.3	13.2	9.7	14	320.3	31.5	9.8	8.4
12	10	310.1	16.5	5.3	5.2	16	325.1	43.8	13.5	11.0
13	11	332.7	25.4	7.6	7.7	14	369.1	33.4	9.0	8.9
14	-	-	-	-	-	4	377.3	63.7	16.9	36.8

TABLE 3.2.21 Girth, Calf, Maximum (mm)

	MALES (F= 23.0)					FEMALES (F= 16.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	257.4	25.9	10.1	8.6	13	256.5	16.8	6.6	4.7
9	32	265.2	18.5	7.0	3.3	35	263.4	22.7	8.6	3.8
10	30	269.8	22.0	8.2	4.0	29	282.5	26.1	9.3	4.9
11	19	298.2	39.4	13.2	9.0	15	296.7	26.0	8.8	6.7
12	16	296.5	25.7	8.7	6.4	16	300.0	35.7	11.9	8.9
13	28	307.1	22.4	7.3	4.2	14	333.0	24.8	7.5	6.6
14	21	317.2	22.4	7.1	4.9	4	324.0	49.8	15.4	24.9
15	23	332.3	39.2	11.8	8.2	-	-	-	-	-
16	13	339.4	21.5	6.3	6.0	-	-	-	-	-

TABLE 3.2.22 Girth, Ankle (mm)

	MALES (F= 86)					FEMALES (F= 12.8)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	165.2	12.8	7.7	4.3	13	166.5	11.6	7.0	3.2
9	32	176.6	13.2	7.5	2.3	35	171.0	12.2	7.1	2.1
10	30	181.5	15.1	8.3	2.8	29	180.2	16.6	9.2	3.1
11	19	189.2	22.2	11.7	5.1	15	189.1	18.8	10.0	4.9
12	9	191.1	14.6	7.6	4.9	16	188.7	19.4	10.3	4.8
13	12	203.2	19.0	9.3	5.5	14	208.6	15.9	7.6	4.3
14	3	197.7	11.0	5.5	6.3	4	201.0	25.3	12.6	12.6
15	7	206.1	13.3	6.4	5.0	-	-	-	-	-
16	2	225.5	2.1	0.9	1.5	-	-	-	-	-

TABLE 3.2.23 Length, Total upper limb (mm)

	MALES (F= 62.5)					FEMALES (F= 31.8)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	562.8	36.4	6.5	12.1	13	542.5	23.5	4.3	6.5
9	32	574.4	24.6	4.3	4.3	35	575.6	28.1	4.9	4.8
10	30	593.9	36.0	6.1	6.6	29	590.8	31.6	5.4	5.9
11	19	623.9	45.3	7.3	10.4	15	625.0	28.6	4.6	7.4
12	16	648.9	36.3	5.6	9.1	16	633.9	40.5	6.4	10.1
13	28	674.0	42.3	6.3	8.0	14	673.4	28.7	4.3	7.7
14	21	713.0	46.1	6.5	10.1	4	673.3	52.3	7.8	26.2
15	23	726.5	44.7	6.2	9.3	-	-	-	-	-
16	13	758.5	32.8	4.3	9.1	-	-	-	-	-

TABLE 3.2.24 Length, Forearm (mm)

	MALES (F= 58.1)					FEMALES (F= 23.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	188.2	14.4	7.6	4.8	13	180.2	9.6	5.3	2.7
9	32	194.2	10.4	5.4	1.8	35	193.9	10.8	5.6	1.8
10	30	199.7	12.4	6.2	2.3	29	196.3	13.2	6.7	2.5
11	19	208.8	16.3	7.8	3.7	15	209.2	11.2	5.3	2.9
12	16	222.7	14.5	6.5	3.6	16	210.0	13.5	6.4	3.4
13	28	229.8	13.8	6.0	2.6	14	227.6	13.9	6.1	3.7
14	21	240.7	17.2	7.1	3.8	4	221.3	16.6	7.5	8.3
15	23	248.6	13.8	5.6	2.9	-	-	-	-	-
16	13	256.2	17.3	6.8	4.8	-	-	-	-	-

TABLE 3.2.25 Length, Forearm with hand (mm)

	MALES (F= 66.6)					FEMALES (F= 28.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	318.0	20.1	6.3	6.7	13	312.7	15.1	4.8	4.2
9	32	332.7	15.9	4.8	2.8	35	331.7	15.3	4.6	2.6
10	30	341.5	20.6	6.0	3.8	29	340.3	20.4	6.0	3.8
11	19	360.3	24.5	6.8	5.6	15	358.6	19.6	5.5	5.1
12	16	375.3	20.9	5.6	5.2	16	362.3	20.0	5.5	5.0
13	28	386.9	24.5	6.3	4.6	14	389.9	19.2	4.9	5.1
14	21	411.1	25.9	6.3	5.7	4	383.0	29.1	7.6	14.6
15	23	421.3	21.1	5.0	4.4	-	-	-	-	-
16	13	436.5	23.3	5.3	6.4	-	-	-	-	-

TABLE 3.2.26 Length, Upper arm (mm)

	MALES (F= 35.8)					FEMALES (F= 21.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	244.8	20.1	8.2	6.7	13	228.5	12.7	5.6	3.5
9	32	241.7	14.0	5.8	2.5	35	244.3	13.9	5.7	2.4
10	30	252.4	19.1	7.6	3.5	29	253.3	14.5	5.7	2.7
11	19	263.6	22.2	8.4	5.1	15	267.3	15.4	5.8	4.0
12	16	273.6	16.6	6.1	4.1	16	270.4	14.9	5.5	3.7
13	28	287.1	20.9	7.3	3.9	14	289.1	17.9	6.2	4.8
14	21	301.9	24.5	8.1	5.3	4	292.8	28.2	9.6	14.1
15	23	305.2	33.2	10.9	6.9	-	-	-	-	-
16	13	322.1	13.1	4.1	3.6	-	-	-	-	-

TABLE 3.2.27 Length, Hand (mm)

	MALES (F= 51.3)					FEMALES (F= 21.9)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	129.8	8.8	6.7	2.9	13	133.6	8.0	6.0	2.2
9	32	138.5	7.6	5.5	1.3	35	139.2	7.3	5.2	1.2
10	30	141.8	10.3	7.2	1.9	29	146.4	8.6	5.9	1.6
11	19	151.5	9.3	6.1	2.1	15	152.1	9.8	6.4	2.5
12	16	152.6	8.8	5.7	2.2	16	159.4	17.4	10.9	4.4
13	28	157.1	12.7	8.1	2.4	14	164.9	8.6	5.2	2.3
14	21	170.4	11.5	6.7	2.5	4	162.8	12.6	7.7	6.3
15	23	172.7	9.5	5.5	2.0	-	-	-	-	-
16	13	180.2	8.5	4.7	2.4	-	-	-	-	-

TABLE 3.2.28 Length, Upper leg (mm)

	MALES (F= 46.1)					FEMALES (F= 15.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	339.3	32.0	9.4	10.7	13	340.5	24.9	7.3	6.9
9	32	343.8	23.2	6.8	4.1	35	352.3	18.0	5.1	3.0
10	30	349.0	20.3	5.8	3.7	29	361.9	24.0	6.6	4.5
11	18	371.4	23.8	6.4	5.6	15	380.0	22.8	6.0	5.9
12	16	390.5	26.3	6.7	6.6	16	386.8	23.0	6.0	5.8
13	28	405.1	29.1	7.2	5.5	14	408.0	23.4	5.7	6.3
14	21	424.1	29.3	6.9	6.4	4	379.8	33.7	8.9	16.9
15	23	436.7	25.2	5.8	5.2	-	-	-	-	-
16	13	446.3	41.9	9.4	11.6	-	-	-	-	-

TABLE 3.2.29 Length, Tibia (mm)

	MALES (F= 67.5)					FEMALES (F= 21.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	283.7	20.5	7.2	6.8	13	278.7	17.2	6.2	4.8
9	32	297.3	17.5	5.9	3.1	35	300.7	20.8	6.9	3.5
10	30	305.1	20.5	6.7	3.7	29	310.8	20.8	6.7	3.9
11	19	326.2	25.7	7.9	5.9	15	330.1	19.4	5.9	5.0
12	16	346.1	23.8	6.9	5.9	16	336.5	17.8	5.3	4.5
13	28	357.3	24.8	6.9	4.7	14	348.3	22.4	6.4	6.0
14	21	376.8	21.7	5.8	4.7	4	356.8	25.9	7.3	13.0
15	23	389.7	21.4	5.5	4.5	-	-	-	-	-
16	13	391.5	19.8	5.0	5.5	-	-	-	-	-

TABLE 3.2.30 Length, Foot (mm)

	MALES (F= 53.7)					FEMALES (F= 21.5)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	198.9	11.1	5.6	3.7	13	197.4	7.0	3.6	1.9
9	32	207.7	10.1	4.8	1.8	35	206.8	11.0	5.3	1.9
10	30	215.1	12.1	5.6	2.2	29	214.4	10.0	4.7	1.9
11	19	225.3	15.7	7.0	3.6	15	224.9	11.7	5.2	3.0
12	16	236.7	13.0	5.5	3.3	16	225.9	14.0	6.2	3.5
13	28	239.8	16.3	6.8	3.1	14	233.9	9.6	4.1	2.6
14	21	251.8	11.4	4.5	2.5	4	236.8	12.3	5.2	6.1
15	23	254.0	12.3	4.9	2.6	-	-	-	-	-
16	13	260.8	10.5	4.0	2.9	-	-	-	-	-

TABLE 3.2.31 Length, Total lower limb (mm)

	MALES (F= 61.6)					FEMALES (F= 29.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	669.3	44.3	6.6	14.8	13	648.1	32.0	4.9	8.9
9	31	690.4	34.2	5.0	6.1	35	696.6	36.6	5.2	6.2
10	30	710.0	48.5	6.8	8.8	29	718.3	43.3	6.0	8.0
11	19	767.4	59.5	7.7	13.6	15	766.9	38.2	5.0	9.9
12	15	793.0	49.8	6.3	12.9	16	771.0	41.6	5.4	10.4
13	27	818.6	48.2	5.9	9.3	14	810.7	45.2	5.6	12.1
14	21	857.8	50.9	5.9	11.1	4	824.8	53.0	6.4	26.5
15	23	881.7	47.4	5.4	9.9	-	-	-	-	-
16	13	899.0	40.6	4.5	11.2	-	-	-	-	-

TABLE 3.2.32 Breadth, Shoulder (mm)

	MALES (F= 29.0)					FEMALES (F= 33.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	287.3	17.8	6.2	5.9	13	283.2	13.1	4.6	3.6
9	32	292.8	14.4	4.9	2.5	35	289.5	13.9	4.8	2.4
10	30	301.8	17.3	5.7	3.2	29	300.0	15.2	5.1	2.8
11	19	311.1	22.0	7.1	5.0	15	312.3	17.8	5.7	4.6
12	16	328.8	19.2	5.8	4.8	16	322.1	21.5	6.7	5.4
13	28	331.1	23.3	7.0	4.4	14	346.4	14.0	4.0	3.7
14	21	343.0	23.6	6.9	5.1	4	346.0	6.2	1.8	3.1
15	23	345.6	33.0	9.5	6.9	-	-	-	-	-
16	13	371.8	19.5	5.2	5.4	-	-	-	-	-

TABLE 3.2.33 Breadth, Hip (mm)

	MALES (F= 31.3)					FEMALES (F= 23.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	203.9	10.9	5.3	3.6	13	201.2	8.5	4.2	2.4
9	32	209.1	10.4	5.0	1.8	35	213.2	17.0	7.9	2.9
10	30	215.6	14.2	6.6	2.6	29	217.7	16.4	7.5	3.0
11	19	225.2	19.1	8.5	4.4	15	235.1	18.0	7.7	4.7
12	16	229.1	21.5	9.4	5.4	16	238.1	21.7	9.1	5.4
13	28	242.1	25.5	10.6	4.8	14	265.8	17.8	6.7	4.8
14	21	246.3	16.1	6.5	3.5	4	255.8	24.0	9.4	12.0
15	23	257.0	17.3	6.7	3.6	-	-	-	-	-
16	13	273.9	16.3	6.0	4.5	-	-	-	-	-

TABLE 3.2.34 Breadth, Hand (mm)

	MALES (F= 52.0)					FEMALES (F= 22.1)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	74.6	6.2	8.3	2.1	13	72.7	3.8	5.2	1.0
9	32	77.7	5.0	6.4	0.9	35	76.2	4.8	6.3	0.8
10	30	80.6	4.6	5.8	0.8	28	79.1	4.2	5.3	0.8
11	19	84.4	5.8	6.9	1.3	15	84.5	5.7	6.8	1.5
12	16	88.0	5.3	6.0	1.3	16	83.5	5.1	6.1	1.3
13	27	90.6	6.7	7.4	1.3	14	89.1	6.0	6.8	1.6
14	21	95.2	6.8	7.2	1.5	4	89.0	5.4	6.1	2.7
15	23	99.1	5.8	5.9	1.2	-	-	-	-	-
16	13	101.5	4.5	4.5	1.3	-	-	-	-	-

TABLE 3.2.35 Breadth, Foot (mm)

	MALES (F= 48.6)					FEMALES (F= 16.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	73.3	7.1	9.7	2.4	13	72.8	4.1	5.6	1.1
9	32	77.6	4.3	5.6	0.8	35	75.7	4.6	6.1	0.8
10	30	77.9	4.6	5.9	0.8	29	79.1	5.8	7.4	1.1
11	19	82.9	5.9	7.1	1.4	15	81.1	4.9	6.0	1.3
12	16	86.6	4.7	5.4	1.2	16	82.1	5.6	6.8	1.4
13	28	88.9	5.1	5.7	1.0	14	88.6	4.0	4.5	1.1
14	21	93.3	5.0	5.3	1.1	4	84.5	3.1	3.7	1.6
15	22	94.1	5.7	6.1	1.2	-	-	-	-	-
16	13	96.5	4.1	4.3	1.1	-	-	-	-	-

TABLE 3.2.36 Breadth, Chest (mm)

	MALES (F= 8.8)					FEMALES (F= 17.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	200.1	16.9	8.5	5.6	13	195.8	11.9	6.1	3.3
9	32	207.6	13.3	6.4	2.3	35	200.7	16.6	8.3	2.8
10	30	210.6	14.9	7.1	2.7	29	201.4	13.5	6.7	2.5
11	19	208.6	19.7	9.5	4.5	15	212.3	13.6	6.4	3.5
12	16	224.0	17.3	7.7	4.3	16	222.8	20.3	9.1	5.1
13	28	226.1	15.7	7.0	3.0	14	240.6	14.9	6.2	4.0
14	21	233.2	53.1	22.8	11.6	4	226.0	15.5	6.9	7.8
15	23	241.1	16.0	6.6	3.3	-	-	-	-	-
16	13	246.4	14.7	6.0	4.1	-	-	-	-	-

TABLE 3.2.37 Index, Hip/Shoulder breadth

	MALES (F= 1.7)					FEMALES (F= 2.1)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	71.0	2.7	3.8	0.9	13	71.1	3.6	5.0	1.0
9	32	71.5	3.1	4.3	0.5	35	73.7	4.5	6.1	0.8
10	30	71.5	3.9	5.5	0.7	29	72.6	3.9	5.4	0.7
11	19	72.4	3.4	4.7	0.8	15	75.4	5.4	7.2	1.4
12	16	69.8	6.0	8.6	1.5	16	73.9	4.2	5.6	1.0
13	28	73.2	6.3	8.6	1.2	14	76.8	4.6	6.0	1.2
14	21	72.1	5.6	7.8	1.2	4	73.9	6.3	8.6	3.2
15	23	75.0	8.7	11.6	1.8	-	-	-	-	-
16	13	73.7	2.8	3.8	0.8	-	-	-	-	-

TABLE 3.2.38 Index, Sitting height/stature

	MALES (F= 11.0)					FEMALES (F= 1.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	54.0	2.1	3.9	0.7	12	53.4	0.9	1.7	0.3
9	29	53.1	1.4	2.5	0.3	34	52.9	1.0	1.9	0.2
10	30	53.2	1.2	2.2	0.2	29	53.3	1.3	2.4	0.2
11	19	52.8	0.9	1.6	0.2	15	52.8	1.2	2.3	0.3
12	15	52.2	1.1	2.0	0.3	16	52.4	1.1	2.1	0.3
13	27	51.8	1.0	2.0	0.2	17	53.7	1.2	2.2	0.3
14	21	50.8	1.6	3.1	0.3	10	53.4	1.2	2.2	0.4
15	23	51.5	1.6	3.1	0.3	12	53.3	1.6	3.0	0.5
16	13	51.6	1.1	2.1	0.3	5	53.5	1.9	3.4	0.8

TABLE 3.2.39 CG, Whole body

	MALES (F= 9.1)					FEMALES (F= 4.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	61.7	4.5	7.2	1.5	10	59.0	6.3	10.7	2.0
9	29	59.9	4.4	7.4	0.8	32	59.6	4.2	7.1	0.7
10	30	56.5	2.2	3.8	0.4	28	56.5	3.0	5.4	0.6
11	16	56.1	1.3	2.2	0.3	12	56.3	2.4	4.2	0.7
12	15	55.8	0.6	1.1	0.2	11	55.8	0.6	1.0	0.2
13	22	56.0	0.7	1.3	0.2	11	54.8	2.1	3.8	0.6
14	4	56.3	0.9	1.5	0.4	2	55.4	1.5	2.7	1.1
15	7	55.2	1.1	1.9	0.4	-	-	-	-	-
16	2	55.9	0.1	0.2	0.1	-	-	-	-	-

TABLE 3.2.40 CG, Hand

	MALES (F= 1.0)					FEMALES (F= 3.0)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	66.3	1.9	2.8	0.6	12	65.9	1.5	2.3	0.4
9	31	66.1	1.0	1.6	0.2	31	65.8	1.3	1.9	0.2
10	27	65.7	0.9	1.5	0.2	28	65.8	0.9	1.4	0.2
11	19	66.2	1.1	1.7	0.3	14	66.6	0.8	1.2	0.2
12	16	66.3	1.3	1.9	0.3	11	66.8	1.2	1.7	0.3
13	23	66.4	1.1	1.7	0.2	15	66.3	0.8	1.1	0.2
14	5	66.7	1.0	1.5	0.5	10	66.6	0.7	1.1	0.2
15	7	66.1	0.7	1.0	0.3	10	66.6	1.0	1.4	0.3
16	2	66.7	0.8	1.1	0.5	5	67.3	0.4	0.6	0.2

TABLE 3.2.41 CG, Forearm

	MALES (F= 1.3)					FEMALES (F= 2.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	58.0	1.7	3.0	0.6	12	55.9	3.1	5.6	0.9
9	32	57.6	1.8	3.2	0.3	33	57.6	1.9	3.3	0.3
10	27	57.9	2.6	4.5	0.5	28	58.0	1.5	2.6	0.3
11	19	58.1	2.6	4.4	0.6	14	59.0	1.6	2.7	0.4
12	16	58.5	3.1	5.2	0.8	11	58.0	2.0	3.5	0.6
13	23	59.2	1.8	3.1	0.4	16	57.7	2.0	3.4	0.5
14	5	58.5	1.7	3.0	0.8	10	58.7	3.3	5.6	1.0
15	7	58.7	1.1	1.8	0.4	11	58.9	2.0	3.4	0.6
16	2	60.6	0.3	0.5	0.2	5	57.1	2.4	4.3	1.1

TABLE 3.2.42 CG, Upper arm

	MALES (F= 3.8)					FEMALES (F= 2.9)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	53.5	2.5	4.6	0.8	12	54.1	2.2	4.1	0.6
9	31	54.6	1.7	3.2	0.3	33	55.2	2.5	4.6	0.4
10	27	55.7	1.4	2.4	0.3	28	55.2	1.4	2.5	0.3
11	19	55.6	0.9	1.7	0.2	14	55.7	1.0	1.8	0.3
12	16	55.2	1.8	3.2	0.4	11	54.4	1.8	3.3	0.5
13	23	55.6	1.6	2.8	0.3	16	54.3	2.3	4.3	0.6
14	5	56.7	1.5	2.7	0.7	10	57.4	1.9	3.3	0.6
15	7	55.1	2.1	3.9	0.8	11	55.6	1.6	2.9	0.5
16	2	58.2	1.8	3.2	1.3	5	55.6	1.5	2.7	0.7

TABLE 3.2.43 CG, Forearm with hand

	MALES (F= 1.2)					FEMALES (F= 4.2)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	61.4	1.0	1.7	0.3	11	61.0	0.9	1.5	0.3
9	31	61.4	1.1	1.8	0.2	33	62.0	1.6	2.7	0.3
10	27	61.6	1.2	2.0	0.2	28	62.2	0.9	1.5	0.2
11	19	62.1	1.5	2.4	0.3	14	62.8	1.1	1.8	0.3
12	16	61.7	1.4	2.2	0.3	11	62.0	1.3	2.1	0.4
13	23	61.9	1.1	1.8	0.2	16	62.6	1.6	2.6	0.4
14	5	62.6	1.7	2.8	0.8	10	63.5	1.4	2.2	0.4
15	7	61.6	1.0	1.6	0.4	11	63.4	1.1	1.8	0.3
16	2	62.8	0.4	0.6	0.3	5	62.9	1.3	2.1	0.6

TABLE 3.2.44 CG, Upper arm with forearm

	MALES (F= 6.0)					FEMALES (F= 3.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	56.6	2.0	3.5	0.7	12	56.8	1.8	3.2	0.5
9	31	57.4	1.4	2.4	0.2	33	57.9	2.0	3.5	0.4
10	26	58.2	1.2	2.1	0.2	28	58.4	1.2	2.1	0.2
11	19	58.5	1.3	2.3	0.3	14	59.4	1.3	2.1	0.3
12	16	58.3	1.6	2.7	0.4	11	58.4	1.4	2.3	0.4
13	23	59.0	1.3	2.1	0.3	16	58.7	1.7	2.9	0.4
14	5	60.0	0.6	1.1	0.3	10	59.5	1.7	2.8	0.5
15	7	58.3	1.0	1.8	0.4	11	59.1	1.3	2.3	0.4
16	2	60.2	0.5	0.9	0.4	5	59.5	1.4	2.4	0.6

TABLE 3.2.45 CG, Upper limb

	MALES (F= 6.0)					FEMALES (F= 6.0)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	60.5	1.6	2.7	0.5	12	60.8	1.5	2.4	0.4
9	32	61.0	1.4	2.4	0.3	33	61.9	1.7	2.8	0.3
10	27	61.8	1.2	1.9	0.2	28	62.5	1.2	1.9	0.2
11	19	62.5	1.3	2.0	0.3	14	63.4	1.3	2.1	0.3
12	16	61.9	1.5	2.3	0.4	11	62.4	1.5	2.3	0.4
13	23	62.5	1.1	1.8	0.2	16	63.1	1.7	2.6	0.4
14	5	63.9	1.7	2.6	0.7	10	63.8	1.4	2.2	0.4
15	7	61.9	1.1	1.7	0.4	11	63.4	1.2	1.9	0.4
16	2	63.2	0.8	1.3	0.6	5	64.0	1.3	2.0	0.6

TABLE 3.2.46 CG, Calf

	MALES (F= 0.8)					FEMALES (F= 2.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	4	58.8	2.1	3.6	1.1	5	58.2	1.1	2.0	0.5
9	13	58.3	1.5	2.6	0.4	9	58.0	0.9	1.5	0.3
10	9	59.8	3.7	6.1	1.2	10	58.7	1.4	2.4	0.5
11	12	59.2	1.6	2.8	0.5	8	59.1	1.3	2.3	0.5
12	13	58.8	1.5	2.6	0.4	10	60.3	1.4	2.4	0.4
13	23	59.4	1.7	2.8	0.3	15	59.6	1.7	2.8	0.4
14	5	59.2	1.8	3.0	0.8	7	59.9	1.7	2.9	0.7
15	7	58.9	2.0	3.4	0.7	8	59.7	1.3	2.2	0.5
16	2	57.1	0.7	1.3	0.5	4	59.2	0.9	1.5	0.4

TABLE 3.2.47 CG, Thigh

	MALES (F= 2.1)					FEMALES (F=2.9)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	3	54.2	2.1	3.9	1.2	5	52.8	1.3	2.5	0.6
9	10	53.3	3.3	6.2	1.0	9	53.1	2.5	4.7	0.8
10	8	52.6	3.2	6.1	1.1	9	54.1	2.0	1.9	0.3
11	10	51.4	2.5	4.9	0.8	5	53.3	2.7	5.0	1.2
12	7	55.2	2.8	5.2	1.1	9	56.0	1.0	1.9	0.3
13	12	54.4	2.0	3.7	0.6	11	57.6	2.5	4.1	0.7
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 3.2.48 PMI, Hand (cm^{2}kg)

	MALES (F= 30.7)					FEMALES (F= 32.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	2.2	0.7	31.4	0.23	12	1.8	0.3	16.2	0.09
9	32	2.4	0.4	18.2	0.08	33	2.2	0.4	18.8	0.07
10	27	3.0	0.9	28.7	0.17	28	2.8	0.7	23.6	0.13
11	19	3.5	1.1	31.1	0.25	14	3.4	1.0	29.0	0.26
12	16	4.2	0.9	20.8	0.22	11	3.9	0.9	23.5	0.28
13	23	4.5	1.4	30.8	0.29	16	4.6	1.0	21.6	0.25
14	5	5.5	2.0	36.1	0.88	10	4.7	1.1	22.6	0.34
15	7	7.3	1.3	18.3	0.50	11	4.5	0.8	17.0	0.23
16	2	8.2	2.1	25.1	1.46	5	5.3	1.6	30.1	0.71

TABLE 3.2.49 PMI, Forearm (cm^{2}kg)

	MALES (F= 31.4)					FEMALES (F= 24.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	11.3	3.5	30.9	1.2	12	9.4	3.6	38.3	1.0
9	32	14.3	3.5	24.6	0.6	33	14.0	5.3	38.2	0.9
10	27	16.1	4.9	30.6	0.9	28	15.8	5.1	32.1	1.0
11	19	21.3	8.6	40.3	2.0	14	21.0	6.4	30.4	1.7
12	16	24.0	9.3	38.8	2.3	11	24.7	9.1	37.0	2.8
13	23	26.1	8.6	32.8	1.8	16	29.5	7.5	25.3	1.9
14	5	34.8	9.6	27.5	4.3	10	35.9	13.1	36.5	4.1
15	7	39.4	7.0	17.7	2.6	11	32.1	8.1	25.1	2.4
16	2	68.6	1.9	2.8	1.4	5	37.5	14.2	37.9	6.4

TABLE 3.2.50 PMI, Upper arm (cm^{2}kg)

	MALES (F= 22.0)					FEMALES (F= 33.0)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	26.9	10.9	40.8	3.7	12	26.1	9.0	34.5	2.6
9	32	32.4	8.6	26.6	1.5	33	33.5	11.9	35.6	2.1
10	27	46.1	16.3	35.3	3.1	28	45.6	14.4	31.5	2.7
11	19	55.4	25.5	46.1	5.9	14	54.5	13.9	25.4	3.7
12	16	65.8	24.0	36.5	6.0	11	51.5	14.7	28.6	4.4
13	23	72.0	25.9	36.0	5.4	16	84.2	19.3	22.9	4.8
14	5	80.9	22.6	28.0	10.1	10	87.8	30.7	35.0	9.7
15	7	104.9	33.4	31.8	12.6	11	87.6	21.6	24.7	6.5
16	2	150.1	13.2	8.8	9.3	5	97.7	22.2	22.7	9.9

TABLE 3.2.51 PMI, Forearm with hand (cm^2kg)

	MALES (F= 33.8)					FEMALES (F= 26.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	44.2	13.3	30.1	4.4	12	35.6	9.6	27.0	2.8
9	32	52.5	9.6	18.2	1.7	33	49.6	14.6	29.5	2.5
10	27	61.7	18.1	29.4	3.5	28	59.0	16.8	28.4	3.2
11	19	77.8	30.0	38.5	6.9	14	76.8	24.0	31.3	6.4
12	16	90.6	29.4	32.4	7.3	11	86.3	25.9	29.9	7.8
13	23	100.3	32.5	32.4	6.8	16	103.1	24.4	23.7	6.1
14	5	125.2	41.9	33.5	18.7	10	116.2	37.2	32.0	11.8
15	7	154.7	24.1	15.6	9.1	11	108.3	20.1	18.6	6.1
16	2	240.6	18.5	7.7	13.1	5	126.6	46.7	36.9	20.9

TABLE 3.2.52 PMI, Upper arm with forearm (cm^2kg)

	MALES (F= 28.9)					FEMALES (F= 35.5)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	127.7	36.2	28.4	12.1	12	116.9	23.7	20.2	6.8
9	32	160.6	37.4	23.3	6.6	33	161.6	54.5	33.7	9.5
10	27	206.8	65.5	31.7	12.6	28	203.1	58.2	28.7	11.0
11	19	256.3	105.7	41.2	24.2	14	250.8	63.1	25.2	16.9
12	16	299.1	111.4	37.2	27.9	11	254.6	64.1	25.2	19.3
13	23	326.0	105.9	32.5	22.1	16	373.0	80.0	21.4	20.0
14	5	404.7	118.4	29.3	53.0	10	423.5	140.0	33.1	44.3
15	7	481.4	115.9	24.1	43.8	11	401.4	104.2	25.9	31.4
16	2	777.3	33.9	4.4	24.0	5	460.3	106.9	23.2	47.8

TABLE 3.2.53 PMI, Upper limb (cm^2kg)

	MALES (F= 31.3)					FEMALES (F= 37.5)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	247.5	75.2	30.4	25.1	12	219.5	44.3	20.2	12.8
9	32	301.1	62.6	20.8	11.1	33	293.7	86.3	29.4	15.0
10	27	386.1	116.9	30.3	22.5	28	372.0	100.5	27.0	19.0
11	19	471.2	183.4	38.9	42.1	14	461.0	116.5	25.3	31.1
12	16	556.9	185.8	33.4	46.4	11	476.8	108.5	22.7	32.7
13	23	612.2	195.0	31.9	40.7	16	662.7	134.3	20.3	33.6
14	5	740.8	229.0	30.9	102.4	10	730.7	218.0	29.8	68.9
15	7	915.3	185.3	20.2	70.0	11	695.3	152.1	21.9	45.9
16	2	1385.8	87.8	6.3	62.1	5	802.3	204.9	25.5	91.7

TABLE 3.2.54 PMI, Calf (cm^{2}kg)

	MALES (F= 15.3)					FEMALES (F= 11.1)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	4	52.8	9.7	18.4	4.9	5	63.9	18.6	29.1	8.3
9	13	92.8	25.8	27.8	7.2	9	76.4	16.7	21.9	5.6
10	9	94.1	32.8	34.9	10.9	10	103.1	41.8	40.5	13.2
11	12	124.1	65.5	52.8	18.9	8	128.8	39.0	30.3	13.8
12	13	184.8	55.4	30.0	15.4	10	150.0	53.8	35.9	17.0
13	23	196.1	84.6	43.1	17.6	15	197.3	44.1	22.3	11.4
14	5	256.2	106.7	41.6	47.7	8	213.6	103.8	48.6	36.7
15	7	308.0	47.9	15.6	18.1	8	241.1	77.7	32.2	27.5
16	2	421.9	143.5	34.0	101.4	4	280.8	104.1	37.1	52.0

TABLE 3.2.55 PMI, Thigh (cm^{2}kg)

	MALES (F= 5.6)					FEMALES (F= 5.8)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	3	77.1	14.2	18.4	8.2	5	87.2	23.0	26.4	10.3
9	10	118.7	44.3	37.3	14.0	9	111.4	40.8	36.6	13.6
10	8	110.0	22.9	20.6	8.0	9	159.9	48.3	30.2	16.1
11	10	143.5	61.2	42.6	19.3	5	157.5	42.6	27.0	19.0
12	7	184.1	45.8	24.9	17.3	9	167.3	66.0	39.4	22.0
13	12	208.5	79.8	38.3	23.0	11	279.4	145.0	51.9	43.7

TABLE 3.2.56 RG, Hand

	MALES (F= 1.3)					FEMALES (F= 0.9)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	24.0	0.6	2.7	0.2	12	24.0	0.5	2.1	0.1
9	32	24.1	0.6	2.6	0.1	33	23.9	0.6	2.6	0.1
10	27	23.9	0.4	1.5	0.1	28	24.0	0.6	2.6	0.1
11	19	23.9	0.4	1.7	0.1	14	23.7	0.6	2.6	0.2
12	16	24.3	0.5	2.2	0.1	11	24.1	0.4	1.9	0.1
13	23	24.0	0.4	1.9	0.1	16	23.9	0.3	1.4	0.1
14	5	24.3	0.4	1.6	0.2	10	24.0	0.3	1.3	0.1
15	7	23.9	0.3	1.4	0.1	11	24.1	0.5	2.1	0.2
16	2	24.3	0.2	0.7	0.1	5	23.8	0.4	1.6	0.2

TABLE 3.2.57 RG, Forearm

	MALES (F= 0.8)					FEMALES (F= 1.1)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	28.5	0.6	2.3	0.2	12	28.7	1.5	5.3	0.4
9	32	28.6	1.3	4.5	0.2	33	28.6	1.3	4.4	0.2
10	27	28.9	1.1	3.8	0.2	28	28.7	0.9	3.3	0.2
11	19	28.9	1.2	4.2	0.3	14	28.7	0.9	3.0	0.2
12	16	28.9	1.9	6.7	0.5	11	29.2	1.4	4.8	0.4
13	23	28.4	0.8	2.9	0.2	16	29.0	1.4	4.7	0.3
14	5	28.4	0.8	2.7	0.3	10	29.8	2.5	8.2	0.8
15	7	28.4	0.5	1.8	0.2	11	28.7	0.8	2.9	0.3
16	2	27.4	0.4	1.5	0.30	5	28.2	0.5	1.8	0.2

TABLE 3.2.58 RG, Upper arm

	MALES (F= 0.6)					FEMALES (F= 0.8)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	30.3	0.9	3.0	0.3	12	30.6	0.6	1.9	0.2
9	32	30.4	1.0	3.3	0.2	33	30.6	1.1	3.7	0.2
10	27	30.7	0.7	2.3	0.1	28	30.2	0.8	2.6	0.2
11	19	30.4	0.6	2.0	0.1	14	30.3	0.6	2.0	0.2
12	16	30.4	0.7	2.2	0.2	11	30.4	0.8	2.7	0.2
13	23	30.3	0.8	2.6	0.2	16	30.1	1.2	4.1	0.3
14	5	30.3	0.6	2.0	0.3	10	30.1	0.8	2.5	0.2
15	7	30.6	1.3	4.2	0.5	11	30.1	0.7	2.2	0.2
16	2	30.8	1.6	5.3	1.1	5	30.4	1.0	3.2	0.4

TABLE 3.2.59 RG, Forearm with hand

	MALES (F= 1.0)					FEMALES (F= 1.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	26.4	0.7	2.8	0.2	12	26.0	0.7	2.8	0.2
9	32	26.3	0.4	1.6	0.1	33	26.2	0.5	1.9	0.1
10	27	26.5	0.6	2.1	0.1	28	26.3	0.3	1.2	0.1
11	19	26.4	0.5	1.8	0.1	14	26.3	0.4	1.5	0.1
12	16	26.6	0.5	2.0	0.1	11	26.4	0.6	2.1	0.2
13	23	26.6	0.4	1.6	0.1	16	26.0	0.5	2.0	0.1
14	5	26.1	1.0	3.8	0.4	10	26.2	1.0	3.7	0.3
15	7	26.5	0.4	1.5	0.2	11	26.1	0.8	3.1	0.2
16	2	26.7	0.1	0.5	0.1	5	25.4	0.6	2.2	0.2

TABLE 3.2.60 RG, Upper arm with forearm

	MALES (F= 1.2)					FEMALES (F= 1.8)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	27.9	0.4	1.6	0.1	12	28.4	0.9	3.0	0.2
9	32	28.2	0.7	2.4	0.1	33	28.3	0.8	2.8	0.1
10	27	28.4	0.7	2.5	0.1	28	28.1	0.5	1.9	0.1
11	19	28.2	0.8	2.7	0.2	14	27.9	0.5	1.8	0.1
12	16	28.0	0.8	2.7	0.2	11	28.0	0.7	2.6	0.2
13	23	27.9	0.6	2.3	0.1	16	27.8	0.6	2.3	0.2
14	5	28.0	0.8	2.7	0.3	10	28.4	1.0	3.6	0.3
15	7	28.0	0.5	1.9	0.2	11	27.9	0.4	1.4	0.1
16	2	28.1	0.8	2.7	0.5	5	28.1	0.4	1.6	0.2

TABLE 3.2.61 RG, Upper limb

	MALES (F= 0.8)					FEMALES (F= 2.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	26.3	0.6	2.1	0.2	12	26.4	0.3	1.2	0.1
9	32	26.4	0.5	2.0	0.1	33	26.3	0.7	2.8	0.1
10	27	26.6	0.5	1.8	0.1	28	26.1	0.4	1.6	0.1
11	19	26.3	0.6	2.2	0.1	14	26.0	0.3	1.4	0.1
12	16	26.4	0.4	1.5	0.1	11	26.1	0.7	2.6	0.2
13	23	26.3	0.5	1.8	0.1	16	25.7	0.6	2.3	0.1
14	5	26.1	1.0	3.8	0.4	10	26.1	0.6	2.3	0.2
15	7	26.4	0.5	2.0	0.2	11	25.8	0.6	2.3	0.2
16	2	26.6	0.3	1.0	0.2	5	25.7	0.2	0.7	0.1

TABLE 3.2.62 RG, Calf

	MALES (F= 0.9)					FEMALES (F= 0.9)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	4	26.9	0.1	0.3	-	5	27.0	0.9	3.5	0.4
9	13	27.2	1.2	4.5	0.3	9	27.7	0.9	3.3	0.3
10	9	27.9	1.5	5.4	0.5	10	27.2	0.8	2.8	0.2
11	12	27.4	1.1	4.2	0.3	8	27.1	0.6	2.0	0.2
12	13	27.5	0.8	2.9	0.2	10	26.9	1.0	3.9	0.3
13	23	27.0	0.9	3.5	0.2	15	27.2	0.7	2.7	0.2
14	5	26.8	1.7	6.4	0.8	8	26.8	1.1	4.0	0.4
15	7	27.2	0.7	2.5	0.3	8	27.0	0.6	2.2	0.2
16	2	27.5	0.8	3.0	0.6	4	27.4	0.8	3.0	0.4

TABLE 3.2.63 RG, Thigh

	MALES (F= 1.1)					FEMALES (F= 1.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	3	30.2	1.3	4.4	0.8	5	29.9	0.8	2.8	0.4
9	10	32.2	3.2	9.9	1.0	9	31.0	1.3	4.1	0.4
10	8	31.0	1.4	4.4	0.5	9	31.5	0.9	5.9	0.3
11	10	30.4	2.4	7.7	0.7	5	30.7	1.7	5.7	0.8
12	7	30.9	1.3	4.3	0.5	9	30.5	1.0	3.4	0.3
13	12	30.4	1.5	4.8	0.4	11	32.9	5.2	15.8	1.6

TABLE 3.2.64 Volume, Hand (ml)

	MALES (F= 22.8)					FEMALES (F= 27.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	173.8	34.2	19.7	11.4	12	152.9	14.8	9.6	4.3
9	32	183.2	19.2	10.5	3.4	33	170.2	18.8	11.0	3.3
10	27	202.3	33.0	16.3	6.3	28	191.1	28.1	14.7	5.3
11	19	223.1	43.2	19.4	9.9	14	215.7	36.8	17.0	9.8
12	16	243.2	34.8	14.3	8.7	11	231.9	32.8	14.2	9.9
13	23	253.2	48.2	19.0	10.0	16	254.1	27.9	11.0	7.0
14	5	270.0	54.5	20.2	24.4	10	249.7	38.8	15.6	12.3
15	7	332.4	39.0	11.7	14.7	11	244.7	30.3	12.4	9.1
16	2	356.0	19.8	5.6	14.0	5	273.0	55.7	20.4	24.9

TABLE 3.2.65 Volume, Forearm (ml)

	MALES (F= 18.8)					FEMALES (F= 19.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	387.6	64.4	16.6	21.5	11	348.2	46.5	13.4	14.0
9	32	429.9	60.3	14.0	10.7	33	428.3	95.7	22.3	16.7
10	27	460.2	95.1	20.7	18.3	28	461.6	92.4	20.0	17.5
11	19	544.7	150.1	27.6	34.4	14	540.9	104.8	19.4	28.0
12	16	564.8	133.9	23.7	33.5	11	567.8	140.0	24.7	42.2
13	23	590.9	116.1	19.6	24.2	16	660.7	100.4	15.2	25.1
14	5	709.2	141.8	20.0	63.4	10	704.1	175.4	24.9	55.5
15	7	749.9	79.3	10.6	30.0	11	685.9	145.7	21.2	43.9
16	2	1002.5	7.8	0.8	5.5	5	761.8	157.0	20.6	70.2

TABLE 3.2.66 Volume, Upper arm (ml)

	MALES (F= 15.6)					FEMALES (F= 25.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	637.1	148.0	23.2	49.3	12	602.8	108.1	17.9	31.2
9	32	717.5	132.8	18.5	23.5	33	739.0	171.9	23.3	29.9
10	27	853.5	209.5	24.5	40.3	28	886.2	190.8	21.5	36.1
11	19	1010.5	325.2	32.2	74.6	14	1031.4	190.8	18.5	51.0
12	16	1053.1	289.4	27.5	72.3	11	990.9	208.7	21.1	62.9
13	23	1121.3	244.3	21.8	50.9	16	1321.5	239.1	18.1	59.8
14	5	1319.6	283.9	21.5	126.9	10	1326.7	363.4	27.4	114.9
15	7	1347.3	238.9	17.7	90.3	11	1314.1	284.9	21.7	85.9
16	2	1690.5	3.5	0.2	2.5	5	1478.6	272.0	18.4	121.6

TABLE 3.2.67 Volume, Upper limb (ml)

	MALES (F= 18.2)					FEMALES (F= 26.4)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	1198.4	221.0	18.4	73.7	12	1093.8	126.9	11.6	36.6
9	32	1330.5	196.3	14.7	34.7	33	1337.4	268.5	20.1	46.7
10	27	1516.1	330.4	21.8	63.6	28	1538.8	303.9	19.7	57.4
11	19	1778.1	507.5	28.5	116.4	14	1788.0	310.2	17.4	82.9
12	16	1861.1	449.0	24.1	112.3	11	1790.4	366.0	20.4	110.4
13	23	1965.2	394.0	20.1	82.2	16	2236.3	339.0	15.2	84.8
14	5	2298.8	456.0	19.8	203.9	10	2280.4	559.4	24.5	176.9
15	7	2429.6	311.7	12.8	117.8	11	2244.8	451.9	20.1	136.2
16	2	3049.0	31.1	1.0	22.0	5	2513.2	463.0	18.4	207.1

TABLE 3.2.68 Volume, Calf (ml)

	MALES (F= 13.3)					FEMALES (F= 11.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	4	1016.0	138.3	13.6	69.1	5	1085.8	179.3	16.5	80.2
9	13	1317.9	211.5	16.0	58.6	9	1181.1	200.1	16.9	66.7
10	9	1336.7	253.9	19.0	84.6	10	1438.5	332.6	23.1	105.2
11	12	1577.6	516.8	32.8	149.2	8	1671.4	361.7	21.6	127.9
12	13	1881.2	357.4	19.0	99.1	10	1771.5	491.0	27.7	155.3
13	23	1924.4	407.6	21.2	85.0	15	2177.3	287.4	13.2	74.2
14	5	2112.4	547.5	25.9	244.8	8	2101.3	540.0	25.7	190.9
15	7	2495.0	278.5	11.2	105.3	8	2302.3	532.3	23.1	188.2
16	2	2939.0	298.4	10.2	211.0	4	2485.8	479.8	19.3	239.9

TABLE 3.2.69 Volume, Thigh (ml)

	MALES (F= 6.0)					FEMALES (F= 7.8)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	3	1920.0	294.3	15.3	169.9	5	2160.6	266.1	12.3	119.0
9	10	2461.2	323.9	13.2	102.4	9	2403.9	558.6	23.2	186.2
10	8	2515.8	445.5	17.7	157.5	9	3052.1	658.9	21.6	219.6
11	10	2922.1	922.0	31.6	291.5	5	3110.4	404.0	13.0	180.7
12	7	3134.4	431.1	13.8	163.0	9	3870.1	743.3	25.9	247.8
13	12	3516.5	650.2	18.5	187.7	11	4014.0	914.9	22.8	275.9

TABLE 3.2.70 Ratio, Hand volume

	MALES (F= 5.7)					FEMALES (F= 10.9)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	0.717	0.077	10.7	0.03	12	0.682	0.103	15.1	0.03
9	32	0.668	0.073	11.0	0.01	33	0.628	0.088	14.1	0.01
10	27	0.646	0.062	9.5	0.01	28	0.590	0.059	10.1	0.01
11	19	0.600	0.067	11.1	0.01	13	0.550	0.062	11.2	0.02
12	16	0.609	0.063	10.3	0.02	11	0.577	0.084	14.6	0.03
13	22	0.596	0.047	7.9	0.01	16	0.515	0.070	13.6	0.02
14	5	0.587	0.071	12.1	0.03	10	0.501	0.082	16.5	0.03
15	7	0.619	0.072	11.7	0.03	11	0.487	0.047	9.7	0.01
16	2	0.552	0.009	1.6	0.01	5	0.464	0.046	9.8	0.02

TABLE 3.2.71 Ratio, Forearm volume

	MALES (F= 4.2)					FEMALES (F= 6.3)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	1.61	0.20	12.3	0.07	11	1.51	0.32	16.4	0.08
9	32	1.58	0.22	12.9	0.04	33	1.55	0.16	10.3	0.03
10	27	1.46	0.15	10.3	0.03	28	1.41	0.12	8.4	0.02
11	19	1.44	0.13	9.0	0.03	13	1.38	0.17	12.6	0.05
12	16	1.39	0.09	6.5	0.02	11	1.38	0.10	7.5	0.03
13	22	1.39	0.08	6.0	0.02	16	1.33	0.10	7.4	0.03
14	5	1.55	0.26	16.7	0.12	10	1.38	0.17	12.6	0.05
15	7	1.39	0.04	3.0	0.02	11	1.34	0.08	6.1	0.03
16	2	1.56	0.05	3.2	0.04	5	1.29	0.08	6.3	0.04

TABLE 3.2.72 Ratio, Upper arm volume

	MALES (F= 0.9)					FEMALES (F= 1.4)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	2.62	0.39	15.0	0.13	12	2.66	0.40	15.0	0.12
9	32	2.62	0.40	12.8	0.06	33	2.67	0.33	12.3	0.06
10	27	2.68	0.25	9.1	0.05	28	2.70	0.18	6.7	0.03
11	19	2.64	0.27	10.2	0.06	13	2.64	0.30	11.5	0.08
12	16	2.58	0.19	7.2	0.05	11	2.43	0.25	10.3	0.08
13	22	2.63	0.29	11.1	0.06	16	2.64	0.25	9.6	0.06
14	5	2.88	0.50	17.4	0.22	10	2.57	0.17	6.7	0.05
15	7	2.48	0.31	12.4	0.12	11	2.57	0.15	6.0	0.05
16	2	2.62	0.10	3.7	0.07	5	2.52	0.14	5.4	0.06

TABLE 3.2.73 Ratio, Upper limb volume

	MALES (F= 1.7)					FEMALES (F= 3.7)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	9	4.94	0.51	10.3	0.17	12	4.85	0.62	14.6	0.20
9	32	4.87	0.61	10.5	0.09	33	4.84	0.42	8.7	0.07
10	27	4.78	0.38	7.9	0.07	28	4.70	0.27	5.8	0.05
11	19	4.67	0.32	6.8	0.07	13	4.56	0.44	9.6	0.12
12	16	4.58	0.23	4.9	0.06	11	4.38	0.35	7.9	0.10
13	22	4.62	0.35	7.6	0.08	16	4.48	0.31	6.8	0.08
14	5	5.01	0.74	14.7	0.33	10	4.45	0.34	7.7	0.11
15	7	4.50	0.27	6.0	0.10	11	4.40	0.19	4.3	0.06
16	2	4.73	0.14	2.9	0.10	5	4.27	0.09	2.0	0.04

TABLE 3.2.74 Ratio, Calf volume

	MALES (F= 1.1)					FEMALES (F= 0.6)				
AGE	No.	MEAN	SD	CV	SE	No.	MEAN	SD	CV	SE
8	4	4.32	0.34	7.8	0.17	5	4.64	1.14	24.6	0.51
9	13	4.82	0.82	11.1	0.14	9	4.66	0.55	11.9	0.19
10	9	4.32	0.79	18.2	0.26	10	4.45	0.35	7.8	0.11
11	12	4.19	0.47	11.3	0.14	8	4.41	0.53	11.8	0.18
12	13	4.51	0.37	8.2	0.10	10	4.35	0.32	7.3	0.10
13	22	4.46	0.54	12.1	0.12	15	4.35	0.25	5.8	0.06
14	5	4.54	0.44	9.6	0.19	8	4.30	0.53	12.4	0.19
15	7	4.63	0.28	6.0	0.10	8	4.41	0.36	8.1	0.13
16	2	4.55	0.28	6.2	0.20	4	4.36	0.40	9.1	0.20

TABLE 3.3 Student's 't' test for the means between sexes

	AGES							
Variables	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Endomorphy	-1.22	-1.48	-1.69	-0.59	-0.70	-2.34	-	-
Mesomorphy	0.64	2.32	0.51	0.95	0.05	0.06	-	-
Ectomorphy	0.21	-0.57	1.97	0.37	0.80	3.19	1.95	1.90
Weight	0.56	0.32	-0.74	0.00	0.38	-2.46	-0.55	0.53
Stature	1.32	0.11	0.46	-0.49	1.62	-0.47	1.27	2.63
Sitting height	1.40	0.14	0.27	-0.54	1.60	-2.80	-0.74	0.16
Skinfold, Triceps	-0.91	-1.44	-2.87	-0.39	-0.54	-2.64	-	-
Skinfold, Subscapular	-0.74	-1.29	-1.79	-0.33	0.05	-2.03	-	-
Skinfold, Suprailiac	-1.48	-1.51	0.48	-0.36	-0.77	-1.37	-	-
Skinfold, Calf	-2.50	-2.20	-3.40	-0.58	0.34	-1.42	-	-
Bicondylar diameter, Humerus	1.97	2.10	2.75	0.03	1.81	1.37	-	-
Bicondylar diameter, Femur	2.16	2.88	2.23	1.12	2.72	0.86	-	-
Girth, Upper arm, Maximum	0.77	0.84	-0.93	-0.10	-0.32	-0.59	-	-
Girth, Forearm, Proximal	1.51	0.88	0.22	0.05	-0.93	-0.39	-	-
Girth, Wrist	0.69	1.42	0.63	-0.74	1.17	-1.85	-	-
Girth, Thigh, Proximal	-0.74	-1.16	-2.96	-0.79	-0.44	-3.87	-	-
Girth, Thigh, Distal	-0.47	-0.57	-1.31	0.07	-0.80	-	-	-
Girth, Calf, Maximum	0.26	0.51	-2.02	0.08	-0.07	-3.22	-	-
Girth, Ankle	0.19	1.89	0.24	-0.01	0.47	-0.67	-	-
Length, Total upper limb	1.40	0.10	0.40	-0.06	1.26	0.19	-	-
Length, Forearm	1.44	0.37	1.01	-0.11	2.72	0.63	-	-
Length, Forearm with hand	0.81	0.51	0.23	0.19	2.04	-0.25	-	-
Length, Upper arm	1.76	-0.54	-0.21	-0.12	0.56	-0.14	-	-
Length, Hand	0.28	0.59	-0.56	-0.15	-0.62	-1.72	-	-
Length, Thigh	-0.15	-1.55	-2.22	-1.09	0.62	-0.36	-	-
Length, Tibia	0.63	-0.48	-1.04	-0.50	1.33	1.24	-	-
Length, Foot	0.58	0.55	0.21	0.03	2.29	1.35	-	-
Length, Total lower limb	1.18	-0.40	-0.63	0.02	1.42	0.67	-	-
Breadth, Shoulder	0.68	1.10	0.38	-0.19	1.21	-2.08	-	-
Breadth, Hip	0.50	-1.03	-0.54	-1.49	-0.95	-2.95	-	-
Breadth, Hand	0.98	1.38	1.23	-0.06	2.50	0.87	-	-
Breadth, Foot	0.54	1.84	-0.90	0.86	2.77	0.30	-	-
Breadth, Chest	0.87	1.90	2.33	-0.56	0.47	-2.80	-	-
Index, Hip/Shoulder breadth	-0.29	-2.21	-1.03	-1.86	-2.25	-1.86	-	-
Index, Sitting height/stature	0.70	0.67	-0.32	0.00	-0.41	-5.46	-4.55	-3.34
CG, Whole body	0.87	0.21	-0.10	-0.17	-0.76	2.42	-	-
CG, Hand	0.46	0.89	-0.47	-1.15	-1.02	0.33	0.04	-1.20
CG, Forearm	1.50	0.02	-0.12	-1.11	0.34	2.47	-0.23	-0.44
CG, Upper arm	-0.49	-1.09	1.52	-0.26	0.78	2.35	-0.88	-0.59
CG, Forearm with hand	0.54	-1.44	-2.21	-1.56	-0.59	-1.30	-1.22	-3.29
CG, Upper arm with Forearm	-0.16	-1.06	-0.69	-1.77	-0.29	0.86	0.61	-1.25
CG, Upper limb	-0.56	-2.22	-2.28	-2.10	-0.97	-1.21	0.07	-2.69
CG, Calf	0.46	0.65	0.95	0.26	-2.34	-0.38	-0.78	-0.93
CG, Thigh	0.99	0.23	-1.48	-1.38	-0.40	-	-	-

TABLE 3.3 Student's 't' test for the means between sexes (Continued)

	AGES							
Variables	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
PMI, Hand	1.56	2.74	0.97	0.46	0.97	0.10	1.04	5.49
PMI, Forearm	1.23	0.48	0.28	0.18	-0.07	-0.81	-0.16	0.95
PMI, Upper arm	0.20	-0.19	0.14	0.03	1.95	-1.22	-0.40	0.84
PMI, Forearm with hand	1.70	1.22	0.59	0.13	0.49	0.08	0.44	3.31
PMI, Upper arm with Forearm	0.88	0.15	0.23	0.12	1.35	-0.99	-0.24	0.78
PMI, Upper limb	1.11	0.65	0.48	0.15	1.44	-0.46	0.11	1.95
PMI, Calf	-0.21	1.76	-0.62	-0.24	1.66	0.21	0.70	1.51
PMI, Thigh	-0.10	0.49	-2.77	-0.57	0.78	-	-	-
RG, Hand	0.20	1.18	-1.14	1.23	0.71	1.05	1.51	-1.33
RG, Forearm	-0.26	0.00	0.62	0.58	-0.50	-1.58	-1.23	-0.34
RG, Upper arm	-1.05	-0.84	2.36	0.56	-0.28	0.43	0.45	0.91
RG, Forearm with hand	1.15	1.67	1.67	0.31	0.99	3.74	-0.24	1.13
RG, Upper arm with Forearm	-1.40	-0.70	2.21	1.45	0.20	0.53	-0.78	0.70
RG, Upper limb	-0.63	0.57	3.54	1.83	1.25	3.49	-0.02	2.15
RG, Calf	-0.39	-1.06	1.42	0.61	1.59	-1.01	0.00	0.46
RG, Thigh	0.97	1.18	-1.12	-0.30	0.85	-	-	-
Volume, Hand	1.87	3.02	1.37	0.55	1.01	0.01	0.96	5.21
Volume, Forearm	1.53	0.30	-0.01	0.10	0.07	-1.76	0.09	0.94
Volume, Upper arm	0.59	-0.32	-0.59	-0.27	0.79	-2.30	0.04	0.19
Volume, Upper limb	1.31	0.14	-0.24	-0.09	0.59	-2.02	0.13	0.85
Volume, Calf	-0.01	1.62	-0.85	-0.49	0.80	-1.95	0.08	0.76
Volume, Thigh	-0.61	0.40	-2.01	-0.53	0.94	-	-	-
Ratio, Hand volume	0.73	1.98	3.06	2.15	1.06	4.23	2.08	4.63
Ratio, Forearm volume	0.29	0.22	1.38	1.31	0.54	2.03	1.52	1.49
Ratio, Upper arm volume	-0.29	-0.98	-0.34	-0.20	1.79	0.00	1.81	-0.64
Ratio, Upper limb volume	0.47	-0.09	1.01	0.75	1.73	1.28	2.09	1.02
Ratio, Calf volume	-0.35	0.17	-0.55	-0.76	1.09	0.80	0.84	1.32

The formula used to calculate 't' in this table is:

$$t = \frac{\bar{x}_m - \bar{x}_f}{\sqrt{\frac{s_m^2(n_m - 1) + s_f^2(n_m - 1)}{n_m + n_f - 2}}\sqrt{\frac{1}{n_m} + \frac{1}{n_f}}}$$

where, s^2 is variance, n is sample size, m is male, f is female.

TABLE 3.4 Significance of tests between means

Variables	Age							
	8	9	10	11	12	13	14	15
Endomorph		↓	↓			↓↓↓	-	-
Mesomorph		↑↑↑					-	-
Ectomorph			↑			↑↑↑	↑↑	↑↑
Weight						↓↓↓		
Stature					↑			↑↑↑
Sitting height	↑				↑	↓↓↓		
Skinfold, Triceps		↓	↓↓↓			↓↓↓	-	-
Skinfold, Subscapular		↓	↓↓			↓↓↓	-	-
Skinfold, Suprailiac	↓	↓				↓	-	-
Skinfold, Calf	↓↓↓	↓↓↓	↓↓↓			↓	-	-
Bicondylar diameter, Humerus	↑↑	↑↑↑	↑↑↑		↑↑	↑	-	-
Bicondylar diameter, Femur	↑↑	↑↑↑	↑↑↑		↑↑↑		-	-
Girth, Upperarmmax							-	-
Girth, Forearm, proximal	↑						-	-
Girth, Forearm, distal		↑				↓↓	-	-
Girth, Thigh, proximal			↓↓↓			↓↓↓	-	-
Girth, Thigh, distal			↓				-	-
Girth, Calf, maximum			↓↓↓			↓↓↓	-	-
Girth, Ankle		↑↑					-	-
Length, Totalupper limb	↑						-	-
Length, Forearm	↑				↑↑↑		-	-
Length, Forearmwithhand					↑↑↑		-	-
Length, Upperarm	↑↑						-	-
Length, Hand							-	-
Length, Upperleg		↓	↓↓↓				-	-
Length, Tibia					↑		-	-
Length, Foot					↑↑↑	↑	-	-
Length, Totallowerlimb					↑		-	-
Breadth, Shoulder						↓↓↓	-	-
Breadth, Hip				↓		↓↓↓	-	-
Breadth, Hand		↑			↑↑↑		-	-
Breadth, Foot		↑↑			↑↑↑		-	-
Breadth, Chest		↑↑	↑↑↑			↓↓↓	-	-
Index, Hip/Shoulder breadth		↓↓↓		↓↓	↓↓↓	↓↓	-	-
Index, Sitting height/stature						↓↓↓	↓↓↓	↓↓↓

TABLE 3.4 Significance of the test between means (Continued)

Variables	Age							
	8	9	10	11	12	13	14	15
CG, Whole body						↑↑↑	-	-
CG, Hand								↓
CG, Forearm	↑					↑↑↑		
CG, Upperarm		↓	↓			↑↑↑		
CG, Forearm with hand		↓	↓↓↓	↓		↓		↓↓↓
CG, Upper arm with Forearm		↓		↓↓				
CG, Upper limb		↓↓↓	↓↓↓	↓↓↓				↓↓↓
CG, Calf					↓↓↓			
CG, Thigh			↓	↓		-	-	-
PMI, Hand	↑	↑↑↑						↑↑↑
PMI, Forearm								↑
PMI, Upperarm					↑↑			
PMI, Forearm with hand	↑↑							↑↑↑
PMI, Upper arm with Forearm					↑			↑
PMI, Upper limb					↑			↑↑
PMI, Calf		↑↑			↑↑			↑↑
PMI, Thigh			↓↓↓			-	-	-
RG, Hand							↑	
RG, Forearm						↓		
RG, Upperarm			↑↑↑					
RG, Forearm with hand		↑	↑			↑↑↑		
RG, Upper arm with Forearm	↓		↑↑↑	↑				
RG, Upper limb			↑↑↑	↑↑		↑↑↑		↑↑↑
RG, Calf			↑		↑			
RG, Thigh						-	-	-
Volume, Hand	↑↑	↑↑↑	↑					↑↑↑
Volume, Forearm	↑↑					↓		
Volume, Upperarm						↓↓↓		
Volume, Upperlimb						↓↓		
Volume, Calf		↑				↓↓		
Volume, Thigh			↓↓			-	-	-
Ratio, Hand volume		↑↑↑	↑↑↑	↑↑↑		↑↑↑	↑↑	↑↑↑
Ratio, Forearm volume			↑			↑↑↑	↑	↑
Ratio, Upperarm volume					↑↑		↑↑	
Ratio, Upperlimb volume					↑↑		↑↑↑	
Ratio, Calf volume								

3.1.1.2 Body weight, stature, and sitting height

Body weight, stature and sitting height are three of the most important anthropometric variables in studies of human biology. For body weight, it was found that by age 11 girls have started their adolescent growth spurt while the boys are still pre-adolescent. Boys then catch up during the following two years. This agrees with the standard growth chart for British children devised by Tanner and Whitehouse (1976). Sitting height demonstrated a similar pattern. It is interesting to note that from age 13 onwards, girls have a greater sitting height/stature index than boys ($P < 0.05$). This indicates sexual dimorphism is present in trunk/leg ratio even at this stage of their growth.

3.1.1.3 Body breadth

Body breadth was assessed by three measurements: shoulder breadth, hip breadth, and chest breadth. A factor common to each of these variable is that, at age 13, girls were observed to have average values significantly larger than boys, despite what the situation was at previous ages. Girls have a greater hip breadth/shoulder breadth index than boys from age 8 to age 13, indicating that the sexual dimorphism of this important shape parameter becomes apparent some years before adolescence. This observation is less obvious in the absolute values of either hip or shoulder breadth, where difference between the sexes was not established until a later stage.

3.1.1.4 Bicondylar diameter: humerus and femur

The results of these measurements indicate that dimensional differences of these bones are an important sexual dimorphism in pre-adolescent children. These differences are in the opposite direction of most other variables which exhibit sexual dimorphism. Here boys are significantly larger than girls in the pre-adolescent years. The earlier adolescent spurt of girls does not reverse this pattern, although the differences between the sexes become less after age 11. This phenomenon (boys have a greater value) is not seen in other size correlated variables. It is concluded that males have structurally larger limb bones, not only as adults, but also prior to adolescence.

3.1.1.5 Limb elements

The average length of the foot in boys is greater than that of girls from ages 8 to 13. At age 12, this difference reaches a peak and then diminishes by at age 13. This may be attributed to effects of the adolescent growth spurt in girls. Foot breadth has a similar pattern except at age 10.

3.1.1.6 Centre of gravity (CG) of the whole body

This variable is expressed as a ratio between the height above the standing surface of the centre of gravity of body and the stature of the subject. Both sexes were found to have a similar value for this variable at all ages except age at 13, when boys had a much larger mean value than girls ($P<0.01$). Because adults are known to have a smaller value for this variable than children, and that females are known generally to have a smaller value than males as adults (Medicine University of China, 1978), it is suggested that this difference is a co-effect of these two factors.

3.1.1.7 Centres of gravity of the limbs

Little difference between the two sexes was found for centre of gravity of each single upper limb element. However, strong sexual dimorphism was found in the multi-element upper limb variables in which the hand was involved. For the centre of gravity of the forearm with hand, girls had a larger mean value than boys in all eight age groups except the youngest one; a strong significant difference was observed at age 15 ($t=3.29$, $P<0.02$). Dimorphism is also shown for the whole upper limb, where girls have a higher mean value in all the age groups. Four of groups (ages 9, 10, 11, 15) were different at the level of $P<0.05$.

3.1.1.8 Principal moments of inertia of the limbs

Boys were found to have a larger average value for the moment of inertia of the hand than girls. This was present for all the age groups, including early adolescence when the girls display a higher growth velocity. However this difference is not as significant as before, and after, this age.

Furthermore, the two multi-element segments of the limbs of which the hand forms a part (ie. forearm with hand and whole upper limb) also display a similar difference between the sexes. The results can be interpreted as showing that growth in early adolescence reduces this sex difference. At age 13, girls had a mean PMI for the upper limb variables which was absolutely different from other age groups. The adolescent growth spurt of girls could explain this result, although the possibility of random error in the sample cannot be totally excluded as a cause.

3.1.1.9 Radius of gyration of the limbs

Again, like the values for the centre of gravity, the difference between the sexes for the mean values of these variables was observed to be maximal in multi-element segments involving the hand. For boys, the forearm with hand of all the age groups was found to have an higher average value for the radius of gyration than for girls. The whole upper limb displayed a similar result. However, there were exceptions at age 8, where the girls had a mean marginally higher than boys, and at age 14, when the values were the same for both sexes.

3.1.1.10 Volume of the limbs

The boys have a higher average hand volume in all the age groups, except again at age 13, where the values for girls and boys are practically the same.

For the hand, at both ends of the age distribution, the significance levels are high (age 8, $P<0.10$; age 9, $P<0.01$; age 15, $P<0.001$). Strong sexual dimorphism is suggested as existing for hand volume and for the ratio of hand volume/ body volume. For the forearm, the sexual difference is more apparent in the ratio of its volume/body volume. Boys have a higher mean value for this ratio than girls in every age group, although it is not true for the absolute value of this variable. Boys also have a higher mean value for the volume of the total upper limb relative to the body volume.

3.1.2 Mean differences among age groups and their tests

The results for 'F' values of the analysis of variance, and the ratio of variations among over within age groups, are given at the top of Tables 3.2.4 to 3.2.74.

3.1.2.1 Somatotype

There was no significant change of the value of somatotype with age except for ectomorphy in girls, for which the 'F' value is 2.7 ($P<0.01$). This suggests that the mean value of ectomorphy becomes smaller as girls grow up, indicating girls changing from being relatively leaner to becoming somewhat fatter. This phenomenon is not observed in boys.

There was suggestion to use Somatotype Attitudinal Distance (SAD) to analyse somatotype difference (Duquet and Hebbelinck, 1977). For the reasons stated in 4.2.6, the SAD is not adopted as an analysis method in this thesis. However, the values of SAD for the sex-age group means were included in Appendix VI.

3.1.2.2 Centre of gravity of whole body

Changes of the position of the centre of gravity of whole body take place in both boys and girls. The relative position moves downwards with age so that older children have a smaller value for this variable than younger ones. This is attributed to allometric growth of the constituent parts of the body.

3.1.2.3 Skinfolds

A change in the skinfold thickness was found for subscapular thickness in girls. 'F' value ($F=2.6$, $P<0.01$) demonstrated significant differences among age groups in girls with the older girls having a higher average value; this trend was not found in boys. However, the calf skinfold thickness in both sexes had differences for the mean value among age groups ($P<0.05$), with a complex, changing, pattern.

3.1.2.4 Index of sitting height/stature

Different patterns were found with growth for this index. Girls, in spite of undergoing an adolescent growth spurt for each of these two individual variables, show little change for the ratio in this period ($F=1.3$, $P>0.05$). In contrast, the boys showed a greater change during this age period ($F=11.0$, $P<0.001$). As boys become older, the ratio reduces its value rapidly until age 14, when it reaches its minimum value before increasing again in older children. In fact, a similar pattern was also displayed by the girls, where the minimum value was reached at age 12. However, in girls the pattern is not as obvious as in boys.

3.1.2.5 Centres of gravity of the limbs

In an interval scheme [0, 1], the mean and standard deviation of a distribution are the most important parameters for describing its properties. As explained earlier, as an analogy, the centre of gravity and the radius of gyration are the variables to describe the mass distribution of a body segment.

There were few variables for centre of gravity of the limbs in which a difference among age groups could be demonstrated. None of the individual segments gave a clear pattern indicating any regular change with age. However, in multi-element segments, the situation is different. Here the results suggest that for all the multi-element segments except for the forearm with hand of boys, older children have a higher mean value for the centres of gravity, although this effect is minor (Tables 3.2.40 to 3.2.47). The result suggests that the proximal segment of the upper limb has more positive relative cross-sectional area growth than the distal segment.

3.1.2.6 Radius of gyration

No limb segment showed age changes for these variables (Tables 3.2.56 to 3.2.63).

3.1.2.7 Volumes of limb segments in ratio to body volume

It was noticed that for both sexes, the relative value of hand and forearm volumes became smaller with age. This trend was stronger for the girls, especially for the hand where the girls have an 'F' value of 10.9. This phenomenon was not seen for the volume of the upper arm.

3.2 CORRELATION AND ALLOMETRY

3.2.1 Correlations of weight and stature with other variables

Correlation coefficients were calculated based on the formula:

$$r_{xy} = r_{yx} = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n} \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{[\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2 / n][\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2 / n]}}$$

The values of correlation coefficients of boys and girls are listed in Table 3.5 and Table 3.6 respectively.

In both sexes, all variables other than the dimensionless ones, and those for the skinfolds, were highly correlated with body size (referring to body weight and stature) and to each other. The variables expressing biomechanical characteristics, volumes and the principal moment of inertia all had very high correlation with body weight. In order to standardise the 'size' variables, the value of cubic root of body weight, rather than its actual value, has been used in the correlation and allometric analyses. Similarly, the fifth roots for principal moment of inertia and cubic root for volume were used in the analyses. All the variables were logged before the calculations were performed.

TABLE 3.5 Correlation and allometry coefficients of boys

	r^1			k^2			
	E*	Weight	Stature	Weight		Stature	
Variables				Z^3	Range	Z^3	Range
Age	0.034	0.827**	0.879**	-	-	-	-
Endomorphy	-0.680**	0.404**	0.122	-	-	-	-
Mesomorphy	-0.699**	0.147	-0.188	-	-	-	-
Ectomorphy	1.000**	-0.326	0.060	-	-	-	-
Weight	-0.326**	1.000**	0.910**	1.00	1.00 - 1.00	1.07	1.00 - 1.14
Stature	0.060	0.910**	1.000**	0.94	0.88 - 1.00	1.00	1.00 - 1.00
Sitting height	-0.040	0.887**	0.940**	0.82	0.76 - 0.89	0.90	0.85 - 0.94
Skinfold, Triceps	-0.596**	0.187	-0.059	16.66	9.46 -68.45	-56.17	39.44 - 16
Skinfold, Subscapular	-0.771**	0.562**	0.270*	6.44	5.31 - 8.16	14.04	9.27 -28.74
Skinfold, Suprailiac	-0.625**	0.402**	0.144	11.47	8.63 -17.06	33.81	17.01 - ∞
Skinfold, Calf	-0.532**	0.338**	0.143	11.41	8.14 -19.01	28.67	14.38 - ∞
Bicondylar diameter, Humerus	-0.197*	0.893**	0.866**	0.95	0.89 - 1.02	1.02	0.94 - 1.11
Bicondylar diameter, Femur	-0.283**	0.868**	0.801**	0.79	0.73 - 0.86	0.83	0.75 - 0.93
Girth, Upper arm, Maximum	-0.420**	0.883**	0.740**	1.53	1.42 - 1.65	1.78	1.56 - 2.03
Girth, Forearm, Proximal	-0.383**	0.940**	0.839**	1.01	0.95 - 1.07	1.11	1.00 - 1.23
Girth, Wrist	-0.259**	0.894**	0.837**	0.93	0.87 - 1.00	1.00	0.91 - 1.10
Girth, Thigh, Proximal	-0.456**	0.868**	0.716**	1.35	1.24 - 1.46	1.55	1.35 - 1.79
Girth, Thigh, Distal	-0.525**	0.910**	0.721**	1.42	1.30 - 1.55	2.03	1.70 - 2.47
Girth, Calf, Maximum	-0.368**	0.907**	0.788**	1.18	1.11 - 1.26	1.30	1.16 - 1.46
Girth, Ankle	-0.354**	0.796**	0.682**	1.19	1.04 - 1.37	1.37	1.13 - 1.67
Length, Total upper limb	-0.017	0.911**	0.971**	1.05	0.98 - 1.12	1.11	1.07 - 1.15
Length, Forearm	-0.032	0.900**	0.948**	1.11	1.04 - 1.19	1.17	1.12 - 1.23
Length, Forearm with hand	-0.006	0.900**	0.957**	1.06	0.98 - 1.13	1.12	1.07 - 1.17
Length, Upper arm	-0.017	0.878**	0.930**	1.13	1.04 - 1.22	1.19	1.13 - 1.26
Length, Hand	0.032	0.852**	0.914**	1.10	1.01 - 1.20	1.16	1.09 - 1.24
Length, Thigh	0.007	0.855**	0.918**	1.11	1.02 - 1.22	1.18	1.11 - 1.26

TABLE 3.5 Correlation and allometry coefficients of boys (Continued)

	r^1			k^2			
	E*	Weight	Stature	Weight		Stature	
Variables				Z^3	Range	Z^3	Range
Length, Tibia	-0.022	0.899**	0.960**	1.18	1.10 - 1.27	1.24	1.19 - 1.30
Length, Foot	-0.008	0.882**	0.935**	0.91	0.84 - 0.98	0.98	0.92 - 1.03
Length, Total lower limb	-0.026	0.898**	0.952**	1.08	1.00 - 1.16	1.14	1.09 - 1.20
Breadth, Shoulder	-0.123	0.850**	0.845**	0.90	0.83 - 0.99	0.97	0.88 - 1.06
Breadth, Hip	-0.225*	0.899**	0.861**	1.03	0.96 - 1.11	1.11	1.02 - 1.20
Breadth, Hand	-0.109	0.906**	0.906**	1.07	1.00 - 1.15	1.15	1.07 - 1.23
Breadth, Foot	-0.138	0.878**	0.868**	0.96	0.88 - 1.03	1.02	0.94 - 1.11
Breadth, Chest	-0.281**	0.693**	0.622**	1.06	0.91 - 1.23	1.17	0.98 - 1.41
Index, Hip/Shoulder breadth	-0.185	0.227*	0.173	-	-	-	-
Index, Sitting height/stature	-0.116	-0.388**	-0.459**	-	-	-	-
CG, Whole body	0.380**	-0.533**	-0.367**	-	-	-	-
CG, Hand	-0.024	0.039	0.083	-	-	-	-
CG, Forearm	-0.075	0.283**	0.271**	-	-	-	-
CG, Upper arm	0.023	0.200*	0.206*	-	-	-	-
CG, Forearm with hand	-0.315**	0.359**	0.219**	-	-	-	-
CG, Upper arm with forearm	-0.308**	0.531**	0.378**	-	-	-	-
CG, Upper limb	-0.462**	0.556**	0.337**	-	-	-	-
CG, Calf	-0.019	-0.100	-0.148	-	-	-	-
CG, Thigh	0.102	0.191	0.361**	-	-	-	-
PMI, Hand	-0.100	0.908**	0.925**	0.86	0.79 - 0.93	0.93	0.87 - 1.00
PMI, Forearm	-0.191	0.904**	0.886**	0.98	0.90 - 1.06	1.07	0.98 - 1.17
PMI, Upper arm	-0.239*	0.899**	0.839**	1.10	1.02 - 1.20	1.21	1.08 - 1.35
PMI, Forearm with hand	-0.162	0.935**	0.928**	0.94	0.88 - 1.00	1.01	0.95 - 1.08
PMI, Upper arm with forearm	-0.223*	0.931**	0.890**	1.01	0.94 - 1.08	1.09	1.00 - 1.19
PMI, Upper limb	-0.196*	0.943**	0.908**	0.97	0.92 - 1.03	1.05	0.97 - 1.14
PMI, Calf	-0.058	0.875**	0.895**	1.26	1.11 - 1.42	1.30	1.17 - 1.45

TABLE 3.5 Correlation and allometry coefficients of boys (Continued)

	r^1			k^2			
	E*	Weight	Stature	Weight		Stature	
Variables				Z^3	Range	Z^3	Range
PMI, Thigh	-0.201	0.786**	0.828**	1.05	0.83 - 1.33	1.28	1.05 1.58
RG, Hand	0.032	-0.011	0.046	-	-	-	-
RG, Forearm	0.094	-0.143	-0.124	-	-	-	-
RG, Upper arm	0.097	-0.132	-0.049	-	-	-	-
RG, Forearm with hand	0.188	0.063	0.173	-	-	-	-
RG, Upper arm with forearm	0.250*	-0.315**	-0.197*	-	-	-	-
RG, Upper limb	0.429**	-0.293**	-0.060	-	-	-	-
RG, Calf	0.007	0.007	0.045	-	-	-	-
RG, Thigh	-0.284*	0.217*	0.113	-	- -	-	-
Volume, Hand	-0.192	0.926**	0.896**	0.79	0.73 - 0.84	0.85	0.78 - 0.92
Volume, Forearm	-0.324**	0.932**	0.836**	0.93	0.87 - 0.99	1.01	0.90 - 1.13
Volume, Upper arm	-0.392**	0.929**	0.785**	1.11	1.04 - 1.19	1.24	1.09 - 1.43
Volume, Upper limb	-0.360**	0.949**	0.830**	0.99	0.93 - 1.05	1.08	0.96 - 1.21
Volume, Calf	-0.195	0.919**	0.866**	1.08	0.98 - 1.18	1.12	0.99 - 1.28
Volume, Thigh	-0.434**	0.912**	0.813**	0.99	0.87 - 1.13	1.21	0.98 - 1.50
Ratio, Hand volume	0.538**	-0.655**	-0.411**	-	-	-	-
Ratio, Forearm volume	0.174	-0.373**	-0.277**	-	-	-	-
Ratio, Upper arm volume	-0.156	0.065	-0.022	-	-	-	-
Ratio, Upper limb volume	0.036	-0.206*	-0.194	-	-	-	-
Ratio, Calf volume	0.256**	-0.038	0.120	-	-	-	-

*E: Ectomorphy

1) r: Correlation coefficient; 2) k: Allometry coefficient; 3) Z: Major axis slope, an estimation of k.

TABLE 3.6 Correlation and allometry coefficients of girls

	r^1			k^2			
	E*	Weight	Stature	Weight		Stature	
Variables				Z^3	Range	Z^3	Range
Age	-0.221*	0.806**	0.866**	-	-	-	-
Endomorphy	-0.586**	0.618**	0.385**	-	-	-	-
Mesomorphy	-0.748**	0.438**	0.066	-	-	-	-
Ectomorphy	1.000**	-0.610**	-0.215*	-	-	-	-
Weight	-0.610**	1.000**	0.887**	1.00	1.00 - 1.00	1.31	1.21 - 1.43
Stature	-0.215*	0.887**	1.000**	0.76	0.70 - 0.83	1.00	1.00 - 1.00
Sitting height	-0.308**	0.895**	0.962**	0.78	0.72 - 0.85	1.03	0.99 - 1.08
Skinfold, Triceps	-0.531**	0.528**	0.313**	5.98	4.63 - 8.39	13.41	8.67 -29.36
Skinfold, Subscapular	-0.601**	0.671**	0.457**	6.08	5.07 - 7.58	11.71	8.67 -17.97
Skinfold, Suprailiac	-0.520**	0.539**	0.332**	8.13	6.34 - 11.29	17.46	11.56 -35.55
Skinfold, Calf	-0.483**	0.514**	0.312**	6.87	5.27 - 9.80	15.01	9.70 -33.04
Bicondylar diameter, Humerus	-0.409**	0.825**	0.812**	0.80	0.71 - 0.91	1.14	1.00 - 1.30
Bicondylar diameter, Femur	-0.538**	0.886**	0.813**	0.82	0.74 - 0.90	1.13	1.00 - 1.29
Girth, Upper arm Maximum	-0.623**	0.917**	0.749**	1.41	1.31 - 1.53	2.14	1.84 - 2.54
Girth, Forearm, Proximal	-0.570**	0.913**	0.790**	0.98	0.91 - 1.07	1.39	1.22 - 1.61
Girth, Wrist	-0.497**	0.842**	0.756**	0.87	0.77 - 0.97	1.24	1.07 - 1.46
Girth, Thigh, Proximal	-0.616**	0.924**	0.776**	1.42	1.32 - 1.53	2.10	1.83 - 2.45
Girth, Thigh, Distal	-0.601**	0.911**	0.776**	1.48	1.36 - 1.61	2.19	1.91 - 2.56
Girth, Calf, Maximum	-0.601**	0.899**	0.744**	1.27	1.17 - 1.39	1.92	1.64 - 2.27
Girth, Ankle	-0.573**	0.845**	0.736**	1.21	1.08 - 1.36	1.79	1.53 - 2.13
Length, Total upper limb	-0.235*	0.848**	0.945**	0.81	0.72 - 0.90	1.11	1.04 - 1.18
Length, Forearm	-0.265**	0.822**	0.899**	0.86	0.76 - 0.98	1.19	1.09 - 1.30
Length, Forearm with hand	-0.223*	0.826**	0.919**	0.80	0.70 - 0.90	1.10	1.02 - 1.19
Length, Upper arm	-0.219*	0.770**	0.863**	0.95	0.82 - 1.10	1.31	1.18 - 1.45
Length, Hand	-0.134	0.720**	0.823**	0.83	0.69 - 0.98	1.19	1.05 - 1.34
Length, Thigh	-0.186	0.754**	0.871**	0.76	0.65 - 0.89	1.08	0.98 - 1.20

TABLE 3.6 Correlation and allometry coefficients of girls (Continued)

Variables	r[1]			k[2]			
	E*	Weight	Stature	Weight		Stature	
				Z[3]	Range	Z[3]	Range
Length, Tibia	-0.206*	0.817**	0.927**	0.93	0.82 - 1.06	1.27	1.18 - 1.36
Length, Foot	-0.264**	0.813**	0.878**	0.68	0.59 - 0.77	0.96	0.87 - 1.06
Length, Total lower limb	-0.200*	0.832**	0.946**	0.85	0.75 - 0.95	1.16	1.09 - 1.23
Breadth, Shoulder	-0.317**	0.835**	0.883**	0.79	0.70 - 0.89	1.10	1.00 - 1.21
Breadth, Hip	-0.493**	0.902**	0.850**	1.12	1.03 - 1.23	1.56	1.40 - 1.74
Breadth, Hand	-0.226*	0.754**	0.778**	0.83	0.71 - 0.97	1.20	1.04 - 1.39
Breadth, Foot	-0.370**	0.791**	0.758**	0.80	0.69 - 0.92	1.15	0.98 - 1.34
Breadth, Chest	-0.370**	0.749**	0.757**	0.97	0.82 - 1.14	1.39	1.19 1.63
Index, Hip/Shoulder breadth	-0.456**	0.511**	0.356**	-	-	-	-
Index, Sitting height/stature	-0.273**	0.123	0.000	-	-	-	-
CG, Whole body	0.349**	-0.482**	-0.275**	-	-	-	-
CG, Hand	-0.153	0.218*	0.278**	-	-	-	-
CG, Forearm	-0.148	0.244**	0.215**	-	-	-	-
CG, Upper arm	0.046	0.044	0.064	-	-	-	-
CG, Forearm with hand	-0.486**	0.565**	0.438**	-	-	-	-
CG, Upper arm with forearm	-0.285**	0.446**	0.355**	-	-	-	-
CG, Upper limb	-0.486**	0.628**	0.473**	-	-	-	-
CG, Calf	-0.158	0.258**	0.209*	-	-	-	-
CG, Thigh	-0.025	0.265*	0.329*	-	-	-	-
PMI, Hand	-0.357**	0.894**	0.910**	0.68	0.63 - 0.74	0.89	0.83 - 0.97
PMI, Forearm	-0.413**	0.893**	0.881**	0.94	0.86 - 1.03	1.23	1.13 - 1.35
PMI, Upper arm	-0.411**	0.898**	0.867**	0.93	0.85 - 1.01	1.21	1.10 - 1.34
PMI, Forearm with hand	-0.404**	0.913**	0.908**	0.82	0.76 - 0.88	1.06	0.98 - 1.15
PMI, Upper arm with forearm	-0.423**	0.938**	0.916**	0.88	0.82 - 0.93	1.13	1.05 - 1.22
PMI, Upper limb	-0.404**	0.938**	0.927**	0.82	0.77 - 0.88	1.06	0.99 - 1.14
PMI, Calf	-0.456**	0.912**	0.930**	0.95	0.86 - 1.05	1.32	1.20 - 1.44

TABLE 3.6 Correlation and allometry coefficients of girls (Continued)

	r¹			k²			
	E*	Weight	Stature	Weight		Stature	
Variables				Z³	Range	Z³	Range
PMI, Thigh	-0.335**	0.747**	0.856**	0.91	0.70 - 1.19	1.43	1.11 - 1.84
RG, Hand	-0.007	-0.017	-0.025	-	-	-	-
RG, Forearm	0.120	-0.077	0.015	-	-	-	-
RG, Upper arm	-0.016	-0.188	-0.174	-	-	-	-
RG, Forearm with hand	0.303**	-0.248*	-0.113	-	-	-	-
RG, Upper arm with forearm	0.297**	-0.393**	-0.260**	-	-	-	-
RG, Upper limb	0.533**	-0.588**	-0.414**	-	-	-	-
RG, Calf	-0.255	0.052	-0.080	-	-	-	-
RG, Thigh	-0.088	0.159	0.239**	-	-	-	-
Volume, Hand	-0.428**	0.909**	0.883**	0.63	0.58 - 0.68	0.81	0.74 - 0.89
Volume, Forearm	-0.531**	0.931**	0.861**	0.90	0.84 - 0.96	1.18	1.07 - 1.31
Volume, Upper arm	-0.549**	0.952**	0.855**	1.00	0.95 - 1.06	1.32	1.19 - 1.46
Volume, Upper limb	-0.547**	0.966**	0.883**	0.90	0.86 - 0.94	1.17	1.07 - 1.28
Volume, Calf	-0.555**	0.949**	0.906**	0.95	0.88 - 1.03	1.33	1.19 - 1.48
Volume, Thigh	-0.508**	0.810**	0.836**	0.88	0.71 - 1.09	1.37	1.04 - 1.85
Ratio, Hand volume	0.654**	-0.839**	-0.640**	-	-	-	-
Ratio, Forearm volume	0.327**	-0.437**	-0.312**	-	-	-	-
Ratio, Upper arm volume	0.173	-0.158	-0.120	-	-	-	-
Ratio, Upper limb volume	0.408**	-0.497**	-0.370*	-	-	-	-
Ratio, Calf volume	0.451**	-0.298**	-0.039	-	-	-	-

*E: Ectomorphy

1) r: Correlation coefficient; 2) k: Allometry coefficient; 3) Z: Major axis slope, an estimation of k.

3.2.1.1 Centre of gravity of the whole body

The position of the centre of gravity of whole body was found to have a negative correlation with body weight, ($r=-0.533$ for boy and -0.482 for girl, $p<0.01$). The centre of gravity of whole body correlated with ectomorphy. The correlation coefficients are 0.380 ($p<0.01$) for boys and 0.349 ($p<0.01$) for girls. This suggests that thin individuals tend to have a higher position of the centre of gravity.

3.2.1.2 Index of hip/shoulder breadth

The index of hip breadth/ shoulder breadth positively correlates with body weight in both boys ($r=0.227$, $p<0.05$) and girls ($r=0.511$, $P<0.001$). It was found to be more strongly correlated with both stature ($r=0.356$, $p<0.01$) and ectomorphy ($r=0.456$, $p<0.01$) in girls than in boys. In the latter case the correlations are not significant.

3.2.1.3 Index of sitting height/stature

Some properties of the index for sitting height/stature have been noted in 3.1.1.2 and 3.1.2.4. The correlations for this index with other variables confirm the pattern shown in the previous sections. For boys, the index correlated with both weight and stature ($r=$ -0.388 and -0.459 respectively, $P<0.001$), but not their quotient (ectomorphy, $r=-0.116$, $p>0.10$). In contrast, for the girls, the index has a correlation with neither body weight ($r=0.123$, $P>0.05$), nor stature ($r=0.000$). However, there is a correlation with ectomorphy ($r=-0.273$, $P<0.01$). This is interpreted as suggesting that leaner girls have a tendency to have longer legs, but that the relative leg lengths of boys depend only on the overall size of the body. It is interesting to note that the signs of the correlation coefficients of this index with body weight are opposite in the two sexes.

3.2.1.4 Centres of gravity of limb segments

The correlation of centre of gravity of individual limb segments with body size was weak, particularly for boys. In boys, only the CG of the forearm ($r=0.283$, $p<0.01$) and upper arm ($r=0.200$, $p<0.05$) demonstrated the weak correlation with body weight. Girls displayed a similar pattern to the boys for the forearm, but they were very different for some of the other variables. The CG of the hand, calf and thigh of girls also correlated with weight and stature but not with ectomorphy. Such correlations were not demonstrated in boys.

All the multi-element segments have relatively high positive correlations with both body weight and stature, as well as with ectomorphy.

3.2.1.5 Radius of gyration of limb segments

The radius of gyration of limbs, generally speaking, either did not correlate with, or was negatively correlated with, body weight (Table 3.7 and 3.8). This was interpreted as indicating that smaller people have a bigger RG for their limbs. Girls have more weight-correlated RG variables than boys. These results suggest that there is a trend for smaller individuals to have a more evenly distributed mass along their limbs. This trend is more obvious between the the limb segments.

3.2.2 Allometry

Allometric coefficients were estimated using the major axis method. Their values with the lower and upper limits of 95 percent range are listed in Table 3.5 (for boys) and Table 3.6 (for girls).

3.2.2.1 Weight

The allometry coefficient of the cubic root of body weight on stature (stature is used as size) was 1.07 for boys and 1.31 for girls. Based on the model of geometrical similarity (McMahon, 1984), this indicated a positive allometry of weight, ie. stature reduces relating the age range between 8 and 16 in relation to the cubic root of body weight. Alternatively this finding suggests that children, especially girls, become more robust rather than thinner. This is in agreement with the results from analysis 3.1.2.1.

3.2.2.2 Hip breadth

Girls have a greater coefficient of bi-iliac breadth on weight than boys' ($P < 0.05$). Boys' bi-iliac breadth displays slightly positive allometry, but girls display a strongly positively allometry. These results suggest that the difference in the index of bi-iliac/shoulder breadth is mainly due to girls' allometry in bi-iliac breadth, and not the other variables.

3.2.2.3 Bicondylar diameter, humerus

The allometry coefficients of the bicondylar diameter of humerus to weight in boys was greater than that for girls ($P < 0.05$). Both sexes showed negative allometry ($k = 0.95$ for boys and 0.80 for girls) with weight. However, if stature was used as the size variable, the result was different. Girls have the higher coefficient (1.14 for girls and 1.02 for boys) with both sexes demonstrating positive allometry ('k' value for boys ranges from 0.94 to 1.11, approximating to isometry). The biomechanical significance of this finding will be discussed later.

It is shown that boys have less shape change for this bone dimension against body weight or stature.

These results for the bicondylar diameter of the humerus are mirrored by those for the femur. However the latter are not as often statistically significant as the former.

3.2.2.4 Girth and length of limbs

When body weight and stature are used as overall size variables, sexual dimorphism in the anthropometric variables of the limbs was observed.

Firstly, if weight is used as a substitute for size, sex differences in the allometric coefficients are not seen in girth, ie. boys and girls have girth growth in the same pattern in relation to body weight. For the limb length variables, boys display positive allometry coefficients (except for the foot length) but girls have negative ones; this suggests a different pattern of allometry. Heavier boys tend to have comparatively longer limbs whereas heavier girls are more likely to have a relatively shorter limb.

When stature is used as the overall size variable, the pattern is different again. There are no differences in length allometry and the girth variables in both sexes have positive allometry in relation to stature. However, girls have higher girth allometric rates than boys.

Irrespective of which variable is used as the size, the proximal ends of the limb girths always display a more positive allometry rate than the mid parts and distal ends which sometimes show isometry, or negative allometry when body weight is used as overall size.

3.2.2.5 Foot length

Foot length, for both sexes, against either weight or stature, is negatively allometric. This is a unique finding for the limb length variables.

3.2.2.6 Inertial characteristics

In the variables for inertial characteristics, only the principal moment of inertia and volume are dimensional, The centre of gravity and radius of gyration are dimensionless, k for CG and GR are thus meaningless and are not listed.

Boys generally have a higher allometry coefficient for moment of inertia and volume variables, if weight is used as the size variable. This is not an unexpected finding, considering that boys have higher allometric coefficients for limb length. The exponent k for moment of inertia ranges from 0.68 to 0.95 for girls and 0.86 to 1.26 for boys. It is shown that the principal moment of inertia increases with a rate about fifth power to linear dimension, agreeing with the theoretical prediction.

3.2.2.7 *Allometric growth before and after the onset of puberty*

The data set of boys and girls were divided by using the age of the commencement of puberty; this was taken as 11.0 years for girls and 13.0 for boys (Tanner and Whitehouse, 1976; Marshall, 1978). It must be pointed out that this method of separating the ages is relatively crude and potentially inaccurate, as many individuals will experience puberty earlier or later, by a considerable period, than the ages specified. However, the method was adopted in the present study as the data set collected was 'cross-sectional' in nature, and it included the morphological variables only. As a consequence, it was considered that no better method could be applied to the data. Any separation of the data based on morphological variables or their combination, would be considered to produce new un-known factors in the following analysis. Furthermore, should any differences be found between the two age groups in the later processing, this separation method is not considered to make the risk of type I statistical error any greater although it might increase the likelihood of type II statistical error.

TABLE 3.7 Allometry coefficients of boys before adolescence using weight or stature as a measure of overall size

Variables	Weight		Stature	
	Z*	Range	Z*	Range
Weight	1.00	1.00 - 1.00	1.23	1.08 - 1.39
Stature	0.81	0.72 - 0.92	1.00	1.00 - 1.00
Sitting height	0.74	0.65 - 0.84	0.93	0.85 - 1.02
Skinfold, Triceps	7.90	5.98 - 11.6	25.7	12.9 - >100
Skinfold, Subscapular	7.69	6.30 - 9.84	22.7	13.4 - 72.8
Skinfold, Suprailiac	11.1	8.61 - 15.4	30.4	17.2 - >100
Skinfold, Calf	9.19	7.07 - 13.1	17.7	11.5 - 38.3
Bicondylar diameter, Humerus	0.90	0.80 - 1.01	1.11	0.96 - 1.29
Bicondylar diameter, Femur	0.89	0.81 - 0.98	1.09	0.96 - 1.24
Girth, Upper arm, Maximum	1.53	1.38 - 1.70	2.36	1.86 - 3.13
Girth, Forearm, Proximal	1.02	0.93 - 1.13	1.37	1.10 - 1.73
Girth, Wrist	0.89	0.79 - 1.00	1.11	0.91 - 1.35
Girth, Thigh, Proximal	1.55	1.40 - 1.72	2.29	1.87 - 2.91
Girth, Thigh, Distal	1.44	1.31 - 1.58	2.08	1.73 - 2.57
Girth, Calf, Maximum	1.26	1.16 - 1.38	1.70	1.42 - 2.06
Girth, Ankle	1.41	1.20 - 1.68	2.03	1.61 - 2.64
Length, Total upper limb	0.91	0.80 - 1.03	1.10	1.03 - 1.18
Length, Forearm	1.06	0.92 - 1.22	1.27	1.16 - 1.40
Length, Forearm with hand	0.94	0.83 - 1.08	1.15	1.05 - 1.26
Length, Upper arm	1.02	0.87 - 1.20	1.24	1.11 - 1.38
Length, Hand	0.95	0.79 - 1.14	1.18	1.03 - 1.35
Length, Thigh	1.10	0.93 - 1.32	1.31	1.16 - 1.47
Length, Tibia	1.17	1.03 - 1.34	1.38	1.28 - 1.49
Length, Foot	0.93	0.81 - 1.06	1.13	1.03 - 1.25
Length, Total lower limb	1.08	0.95 - 1.24	1.30	1.18 - 1.42
Breadth, Shoulder	0.85	0.75 - 0.96	1.04	0.92 - 1.17
Breadth, Hip	0.94	0.84 - 1.05	1.17	1.00 - 1.37
Breadth, Hand	1.00	0.88 - 1.15	1.24	1.08 - 1.44
Breadth, Foot	0.96	0.84 - 1.10	1.20	1.03 - 1.40
Breadth, Chest	1.00	0.82 - 1.23	1.34	1.04 - 1.76
PMI, Hand	0.79	0.71 - 0.87	0.96	0.87 - 1.06
PMI, Forearm	0.93	0.84 - 1.04	1.14	1.01 - 1.29
PMI, Upper arm	1.10	0.99 - 1.23	1.38	1.20 - 1.60
PMI, Forearm with hand	0.86	0.79 - 0.94	1.04	0.94 - 1.15
PMI, Upper arm with forearm	0.97	0.89 - 1.06	1.19	1.06 - 1.34
PMI, Upper limb	0.93	0.85 - 1.01	1.13	1.01 - 1.25
PMI, Calf	1.25	1.05 - 1.51	1.46	1.26 - 1.70
PMI, Thigh	1.08	0.86 - 1.35	1.29	1.06 - 1.58
Volume, Hand	0.74	0.67 - 0.81	0.89	0.79 - 1.00
Volume, Forearm	0.91	0.83 - 0.99	1.11	0.95 - 1.30
Volume, Upper arm	1.14	1.05 - 1.24	1.49	1.25 - 1.79
Volume, Upper limb	0.98	0.91 - 1.06	1.22	1.05 - 1.43
Volume, Calf	1.09	0.95 - 1.25	1.30	1.09 - 1.57
Volume, Thigh	1.01	0.89 - 1.16	1.23	0.98 - 1.56

*Z: Major axis slope as the estimation of allometric coefficient

TABLE 3.8 Allometry coefficients of boys after adolescence using weight or stature as a measure of overall size

Variables	Weight		Stature	
	Z*	Range	Z*	Range
Weight	1.00	1.00 - 1.00	1.21	1.03 - 1.43
Stature	0.83	0.70 - 0.97	1.00	1.00 - 1.00
Sitting height	0.95	0.76 - 1.18	1.10	0.99 - 1.21
Skinfold, Triceps	17.0	9.92 - 58.1	-	-
Skinfold, Subscapular	9.24	6.80 - 14.4	-	-
Skinfold, Suprailiac	13.7	9.98 - 21.9	-	-
Skinfold, Calf	19.4	11.8 - 53.8	-	-
Bicondylar diameter, Humerus	1.11	0.88 - 1.40	1.33	1.03 - 1.75
Bicondylar diameter, Femur	1.07	0.84 - 1.39	1.31	0.92 - 1.93
Girth, Upper arm, Maximum	2.33	1.84 - 3.08	3.47	2.40 - 5.92
Girth, Wrist	1.12	0.96 - 1.31	1.48	1.14 - 1.97
Girth, Forearm, Distal	1.20	0.99 - 1.47	1.41	1.15 - 1.75
Girth, Thigh, Proximal	1.97	1.56 - 2.58	3.01	2.03 - 5.43
Girth, Calf, Maximum	1.60	1.32 - 1.97	2.11	1.56 - 3.07
Girth, Ankle	1.07	0.63 - 1.88	0.87	0.47 - 1.54
Length, Total upper limb	0.94	0.79 - 1.11	1.10	1.00 - 1.22
Length, Forearm	1.02	0.85 - 1.21	1.16	1.03 - 1.30
Length, Forearm with hand	0.94	0.79 - 1.13	1.10	0.99 - 1.22
Length, Upper arm	1.04	0.84 - 1.29	1.24	1.06 - 1.46
Length, Hand	0.99	0.76 - 1.29	1.17	1.01 - 1.37
Length, Thigh	1.08	0.85 - 1.38	1.33	1.16 - 1.55
Length, Tibia	0.85	0.69 - 1.04	1.06	0.94 - 1.18
Length, Foot	0.66	0.50 - 0.85	0.89	0.77 - 1.03
Length, Total lower limb	0.84	0.69 - 1.01	1.02	0.94 - 1.12
Breadth, Shoulder	1.40	1.03 - 1.97	1.66	1.22 - 2.38
Breadth, Hip	1.29	1.05 - 1.61	1.52	1.19 - 2.00
Breadth, Hand	1.01	0.85 - 1.19	1.16	1.00 - 1.36
Breadth, Foot	0.77	0.58 - 1.00	0.88	0.67 - 1.14
Breadth, Chest	2.66	1.92 - 4.10	3.81	2.45 - 7.92
PMI, Hand	0.99	0.74 - 1.31	0.87	0.73 - 1.04
PMI, Forearm	1.15	0.91 - 1.46	1.09	0.88 - 1.37
PMI, Upper arm	1.17	0.83 - 1.68	0.95	0.60 - 1.50
PMI, Forearm with hand	1.07	0.88 - 1.29	1.01	0.86 - 1.18
PMI, Upper arm with forearm	1.09	0.87 - 1.38	0.97	0.73 - 1.29
PMI, Upper limb	1.01	0.85 - 1.21	0.91	0.74 - 1.13
PMI, Calf	1.26	0.99 - 1.62	0.95	0.71 - 1.28
Volume, Hand	0.93	0.71 - 1.21	0.81	0.64 - 1.01
Volume, Forearm	1.07	0.83 - 1.39	1.00	0.75 - 1.35
Volume, Upper arm	1.06	0.71 - 1.61	0.87	0.48 - 1.52
Volume, Upper limb	0.95	0.73 - 1.24	0.85	0.58 - 1.22
Volume, Calf	1.10	0.92 - 1.32	0.84	0.62 - 1.12

*Z: Major axis slope as the estimation of allometric coefficient

TABLE 3.9 Allometry coefficients of girls before adolescence using weight or stature as a measure of overall size

Variables	Weight		Stature	
	Z*	Range	Z*	Range
Weight	1.00	1.00 - 1.00	1.69	1.37 - 2.13
Stature	0.59	0.47 - 0.73	1.00	1.00 - 1.00
Sitting height	0.61	0.50 - 0.74	1.04	0.93 - 1.16
Skinfold, Triceps	6.01	4.79 - 8.04	13.9	9.26 - 27.8
Skinfold, Subscapular	7.19	5.87 - 9.26	14.4	10.4 - 23.5
Skinfold, Suprailiac	10.5	7.81 - 15.8	28.9	16.5 - >100
Skinfold, Calf	6.43	5.25 - 8.26	13.2	9.45 - 21.9
Bicondylar diameter, Humerus	0.86	0.71 - 1.04	1.53	1.23 - 1.96
Bicondylar diameter, Femur	0.85	0.72 - 0.99	1.43	1.16 - 1.78
Girth, Upper arm, Maximum	1.58	1.41 - 1.80	3.08	2.39 - 4.23
Girth, Forearm, Proximal	1.10	0.96 - 1.26	1.97	1.56 - 2.58
Girth, Wrist	1.05	0.85 - 1.30	1.91	1.48 - 2.60
Girth, Thigh, Proximal	1.59	1.42 - 1.79	2.81	2.28 - 3.60
Girth, Thigh, Distal	1.65	1.45 - 1.90	2.92	2.36 - 3.77
Girth, Calf, Maximum	1.24	1.10 - 1.41	2.29	1.82 - 3.01
Girth, Ankle	1.15	0.96 - 1.39	2.03	1.63 - 2.62
Length, Total upper limb	0.68	0.54 - 0.85	1.15	1.02 - 1.29
Length, Forearm	0.83	0.64 - 1.07	1.37	1.18 - 1.61
Length, Forearm with hand	0.73	0.56 - 0.92	1.23	1.07 - 1.41
Length, Upper arm	0.85	0.62 - 1.15	1.46	1.20 - 1.81
Length, Hand	0.78	0.54 - 1.09	1.39	1.14 - 1.71
Length, Thigh	0.76	0.54 - 1.03	1.30	1.09 - 1.56
Length, Tibia	1.04	0.82 - 1.31	1.57	1.41 - 1.75
Length, Foot	0.68	0.54 - 0.83	1.15	0.98 - 1.34
Length, Total lower limb	0.83	0.66 - 1.04	1.32	1.19 - 1.47
Breadth, Shoulder	0.59	0.46 - 0.74	1.09	0.90 - 1.31
Breadth, Hip	1.07	0.90 - 1.28	1.78	1.46 - 2.20
Breadth, Hand	0.86	0.67 - 1.10	1.60	1.22 - 2.18
Breadth, Foot	0.94	0.76 - 1.15	1.65	1.29 - 2.19
Breadth, Chest	0.91	0.61 - 1.35	1.81	1.31 - 2.66
PMI, Hand	0.64	0.54 - 0.76	1.07	0.91 - 1.27
PMI, Forearm	1.03	0.85 - 1.25	1.72	1.43 - 2.10
PMI, Upper arm	1.01	0.83 - 1.22	1.73	1.38 - 2.24
PMI, Forearm with hand	0.84	0.72 - 0.98	1.38	1.18 - 1.63
PMI, Upper arm with forearm	0.86	0.75 - 0.99	1.40	1.18 - 1.66
PMI, Upper limb	0.80	0.70 - 0.91	1.29	1.10 - 1.52
PMI, Calf	0.88	0.58 - 1.31	1.64	1.38 - 2.00
PMI, Thigh	0.95	0.66 - 1.37	1.84	1.33 - 2.72
Volume, Hand	0.61	0.51 - 0.71	1.04	0.87 - 1.24
Volume, Forearm	1.01	0.87 - 1.17	1.71	1.41 - 2.11
Volume, Upper arm	1.12	1.00 - 1.24	1.90	1.56 - 2.37
Volume, Upper limb	0.96	0.88 - 1.05	1.57	1.32 - 1.89
Volume, Calf	0.93	0.70 - 1.24	1.76	1.39 - 2.31
Volume, Thigh	0.97	0.76 - 1.24	1.87	1.35 - 2.79

*Z: Major axis slope as the estimation of allometric coefficient

TABLE 3.10 Allometry coefficients of girls after adolescence using weight or stature as a measure of overall size

Variables	Weight		Stature	
	Z*	Range	Z*	Range
Weight	1.00	1.00 - 1.00	1.61	1.35 - 1.94
Stature	0.62	0.52 - 0.74	1.00	1.00 - 1.00
Sitting height	0.78	0.66 - 0.92	1.22	1.10 - 1.36
Skinfold, Triceps	7.14	5.14 - 11.6	17.2	9.97 - 61.6
Skinfold, Subscapular	7.12	5.61 - 9.68	18.5	11.3 - 50.6
Skinfold, Suprailiac	8.72	6.18 - 14.7	21.2	12.0 - 88.3
Skinfold, Calf	8.55	5.83 - 15.9	21.2	11.4 - >100
Bicondylar diameter, Humerus	0.71	0.45 - 1.04	1.31	0.97 - 1.82
Bicondylar diameter, Femur	0.92	0.75 - 1.11	1.57	1.19 - 2.14
Girth, Upper arm, Maxium	1.55	1.32 - 1.84	3.08	2.22 - 4.81
Girth, Forearm, Proximal	1.03	0.89 - 1.19	1.76	1.36 - 2.35
Girth, Wrist	0.80	0.64 - 0.98	1.37	1.01 - 1.92
Girth, Thigh, Proximal	1.65	1.47 - 1.87	3.13	2.35 - 4.56
Girth, Thigh, Distal	1.73	1.53 - 1.97	3.34	2.51 - 4.89
Girth, Calf, Maximum	1.74	1.45 - 2.12	3.50	2.50 - 5.61
Girth, Ankle	1.73	1.41 - 2.18	3.56	2.48 - 6.02
Length, Total upper limb	0.78	0.59 - 1.01	1.27	1.12 - 1.45
Length, Forearm	0.86	0.65 - 1.13	1.42	1.18 - 1.75
Length, Forearm with hand	0.79	0.59 - 1.04	1.31	1.11 - 1.56
Length, Upper arm	0.95	0.65 - 1.38	1.58	1.28 - 1.99
Length, Hand	0.95	0.59 - 1.53	1.70	1.27 - 2.41
Length, Thigh	0.72	0.48 - 1.02	1.27	1.01 - 1.63
Length, Tibia	0.67	0.47 - 0.91	1.16	0.95 - 1.42
Length, Foot	0.60	0.39 - 0.85	1.10	0.84 - 1.45
Length, Total lower limb	0.63	0.44 - 0.86	1.10	0.95 - 1.28
Breadth, Shoulder	0.82	0.62 - 1.05	1.37	1.09 - 1.75
Breadth, Hip	1.26	1.10 - 1.45	2.18	1.72 - 2.88
Breadth, Hand	0.70	0.33 - 1.26	1.46	1.01 - 2.24
Breadth, Foot	0.78	0.51 - 1.15	1.45	1.05 - 2.10
Breadth, Chest	1.15	0.87 - 1.54	2.00	1.51 - 2.81
PMI, Hand	0.60	0.47 - 0.74	1.00	0.81 - 1.23
PMI, Forearm	0.90	0.74 - 1.09	1.47	1.20 - 1.81
PMI, Upper arm	0.91	0.77 - 1.09	1.48	1.22 - 1.82
PMI, Forearm with hand	0.76	0.63 - 0.91	1.22	1.02 - 1.46
PMI, Upper arm with forearm	0.86	0.74 - 0.99	1.34	1.16 - 1.56
PMI, Upper limb	0.76	0.66 - 0.88	1.19	1.04 - 1.37
PMI, Calf	0.97	0.81 - 1.15	1.52	1.27 - 1.85
PMI, Thigh	1.33	0.68 - 3.08	2.25	1.39 - 4.59
Volume, Hand	0.59	0.49 - 0.71	0.95	0.76 - 1.20
Volume, Forearm	0.97	0.87 - 1.09	1.58	1.30 - 1.95
Volume, Upper arm	1.06	0.96 - 1.18	1.79	1.44 - 2.30
Volume, Upper limb	0.95	0.87 - 1.03	1.53	1.25 - 1.89
Volume, Calf	1.00	0.90 - 1.12	1.61	1.31 - 2.03
Volume, Thigh	1.22	0.76 - 2.05	2.27	1.34 - 5.25

*Z: Major axis slope as the estimation of allometric coefficient

TABLE 3.11 Comparison of allometric coefficients

Variables	Boy (1)-Boy (2)	Girl (1)-Girl (2)	Boy (1)-Girl (1)	Boy (2)-Girl (2)
Bicondylar diameter, Humerus	-9.25**	3.75**	-13.15**	0.36
Bicondylar diameter, Femur	-7.91**	-2.24*	-14.29**	-3.70**
Girth, Upper arm max	-0.74	-0.01	-0.50	0.76
Girth, Forearm, Proximal	-2.52*	1.06	-5.11**	-2.38*
Girth, Wrist	-11.84**	3.33**	-8.36**	0.79
Girth, Thigh, Proximal	-1.06	-0.59	-0.81	-0.20
Girth, Calf, Maximum	-1.85	-1.21	-1.05	-2.94**
Girth, Ankle	3.35**	-4.26**	0.00	-3.99**
Length, Total upper limb	0.13	-6.39**	-4.74**	-8.89**
Length, Forearm	8.74**	-1.28	-5.29**	-8.06**
Length, Forearm with hand	5.20**	-3.16**	-6.52**	-9.11**
Length, Upper arm	-0.06	-1.98*	-8.57**	-6.36**
Length, Hand	0.34	-3.73**	-9.55**	-6.36**
Length, Thigh	-1.47	0.82	0.31	1.85
Length, Tibia	21.84**	9.41**	-6.68**	-5.72**
Length, Foot	24.74**	2.17*	-1.31	-10.05**
Length, Total lower limb	22.01**	10.36**	-1.70	-5.85**
Breadth, Shoulder	-11.58**	-8.84**	-4.03**	3.06**
Breadth, Hip	-10.34**	-1.03	-10.98**	-1.62
Breadth, Hand	4.82**	1.61	-8.23**	-5.58**
Breadth, Foot	18.57**	2.33*	-9.88**	-11.58**
Breadth, Chest	-10.81**	-0.83	-5.62**	4.20**

This table shows the significance tests of allometric coefficients between two groups. Age group before onset of adolescence growth is indicated by (1); whereas after onset of adolescence is indicated by (2).
* $p<0.05$; ** $p<0.01$

It is interesting to observe (Table 3.9 and 3.10) that after the commencement of the adolescent growth spurt girls had an increased rate of growth of most morphological variables. Boys demonstrated fewer changes. As a result, the girls showed generally higher allometric rates than boys. This is interpreted as suggesting that girls have more changes in their body shape, before, and particularly, after the onset of adolescence. This is particularly true if the stature is used as the surrogate for body size.

Table 3.11 listed the results of significance test for the allometric coefficients of morphological variables between age-sex groups. The test method was after Wong (1989). In this table, stature is used as overall body size variables, referring to 'k' values listed in Tables 3.7 to 3.10. The majority of variables show positive allometry against stature, in this case, a negative value indicates that the first group of the two specified at the top of a column has lower allometry value, and *vice versa.*

3.3 PREDICTION OF INERTIAL PROPERTIES USING REGRESSION

Because of practical difficulties in direct measurement of the inertial characteristics of living subjects, it is reasonable to calculate them using more easily obtained anthropometric measurements. This procedure was carried out by Zatziorsky *et al* (1983), who used body weight and stature as independent variables, and Hinriches (1985), who used data collected by Chandler *et al* (1975) to predict values for the moments of inertia of limb segments from standard anthropometric variables, and Ackland *et al* (1988), who created regression equations to predict body segment inertial characteristics of children and youths.

Stepwise regression methods were adopted in this thesis to predict the position of the centre of gravity, moment of inertia, radius of gyration, and volume of the limbs from a pre-selected list of anthropometric variables. The variables in the lists were chosen based on their correlation with the dependent variables.

Body weight (W), stature (S), and sitting height (SH) were in the independent variable lists for the inertial characteristics of both upper and lower limbs. In addition, humeral bicondylar diameter (H), maximum upper arm girth (UG), total upper limb length (ULL), forearm length (FL), length of forearm with hand (FHL), forearm girth (FG), and hand breadth (HB) comprised the independent variables list for the upper limb. Femoral bicondylar diameter (BF), calf girth (CAG), ankle girth (AG), and tibia length (TL) comprised the variable list for the lower limb. In order to unify the dimensions, the fifth roots of moment of inertia, and cubic root of the weight and volume were used in the analysis, rather than the variables themselves. However, for the dimensionless variables, centre of gravity and radius of gyration, original data were used.

A summary of the regression results is listed in Table 3.12 (for boys) and Table 3.13 (for girls).

In Tables 3.12 and 3.13, F is the critical value used to decide whether a variable should enter, or stay, in the prediction equation. 'F_{enter}' and 'F_{stay}' were given equal value in the analysis. Mean residual is the square root of the quotient of the sums of squares residual over the observation number. R is the coefficient of correlation, or multiple correlation (when there is more than one independent variable in the equation).

TABLE 3.12 Summary of the stepwise regression analysis (Boys)

Dependent Variables	F	N	W	S	SH	BH	UG	FG	ULL	FL	FHL	HB	BF	CAG	AG	TL	Mean R.s.	R
CG, HAND	0.15	135	•				•		•	•	•						1.054	0.391
CG, FOREARM	0.15	135				•	•		•								2.111	0.356
CG, FOREARM-HAND	0.15	135					•					•					1.048	0.556
CG, UPPER-FORE ARM	0.15	135					•										1.226	0.527
CG, UPPER LIMB	0.05	135				•	•										1.122	0.670
PMI, HAND	0.01	135		•		•		•		•	•						0.029	0.964
PMI, FOREARM	0.01	135				•	•				•						0.053	0.953
PMI, UPPER ARM	0.01	135	•						•								0.090	0.921
PMI, FOREARM-HAND	0.01	135	•			•	•				•						0.044	0.980
PMI, UPPER-FORE ARM	0.01	135	•				•		•								0.083	0.960
PMI, UPPER LIMB	0.01	135	•			•			•								0.077	0.971
PMI, CALF	0.01	47											•			•	0.118	0.857
RG, FOREARM	0.15	135	•			•	•					•					1.027	0.390
RG, UPPER ARM	0.15	135					•					•					0.776	0.450
RG, FOREARM-HAND	0.10	135					•					•					0.468	0.424
RG, UPPER-FORE ARM	0.15	135			•		•										0.628	0.479
RG, UPPER LIMB	0.05	135					•					•					0.414	0.649
RG, CALF	0.15	47			•								•	•			0.357	0.487
V, HAND	0.01	135	•			•				•	•						0.133	0.961
V, FOREARM	0.01	135					•	•			•						0.207	0.960
V, UPPER ARM	0.01	135	•				•										0.318	0.954
V, UPPER LIMB	0.01	135	•				•		•								0.261	0.974
V, CALF	0.05	66												•		•	0.380	0.954

Abbrivations: W: Weight; S: Stature; SH: Sitting Height; BH: Bicondylar diameter, Humerus; BF: Bicondylar diameter, Femur; UG: Upper arm Girth; FG: Forearm Girth; CAG: Calf Girth; AG: Ankle Girth; ULL: Total upper Limb Length; FL: Forearm Length; FHL: Forearm with Hand Length; HB: Hand Breadth; TL: Tibia Length; R.s.: Mean square of residual

TABLE 3.13 Summary of the stepwise regression analysis (Girls)

Dependent Variables	F	N	W	S	SH	BH	UG	FG	ULL	FL	FHL	HB	BF	CAG	AG	TL	Mean R.s.	R
CG, UPPER ARM	0.05	111		•	•					•		•					1.770	0.358
CG, FOREARM-HAND	0.05	111				•	•										1.081	0.644
CG, UPPER-FORE ARM	0.15	111							•	•		•					1.413	0.499
CG, UPPER LIMB	0.15	111					•			•							1.073	0.715
CG, CALF	0.15	55														•	1.142	0.438
PMI, HAND	0.01	111						•	•	•	•	•					0.023	0.968
PMI, FOREARM	0.01	111						•		•							0.062	0.930
PMI, UPPER ARM	0.01	111	•						•								0.096	0.875
PMI, FOREARM-HAND	0.01	111	•					•			•						0.052	0.963
PMI, UPPER-FORE ARM	0.01	111	•						•								0.082	0.945
PMI, UPPER LIMB	0.01	111	•	•							•						0.081	0.954
PMI, CALF	0.01	49		•											•		0.065	0.965
RG, UPPER ARM	0.15	111					•	•									0.824	0.389
RG, FOREARM-HAND	0.05	111					•					•					0.482	0.409
RG, UPPER-FORE ARM	0.15	111			•		•										0.609	0.509
RG, UPPER LIMB	0.05	111					•					•					0.409	0.728
RG, CALF	0.15	53												•	•		0.651	0.388
V, HAND	0.01	111			•			•		•	•	•					0.106	0.965
V, FOREARM	0.01	111					•	•		•							0.183	0.966
V, UPPER ARM	0.01	111	•				•		•								0.309	0.948
V, UPPER LIMB	0.01	108	•				•	•	•								0.231	0.976
V, CALF	0.05	66			•									•	•	•	0.196	0.986

Abbrivations: W: Weight; S: Stature; SH: Sitting Height; BH: Bicondylar diameter, Humerus; BF: Bicondylar diameter, Femur, UG: Upper arm Girth; FG: Forearm Girth; CAG: Calf Girth; AG: Ankle Girth; ULL: Total upper Limb Length; FL: Forearm Length; FHL: Forearm with Hand Length; HB: Hand Breadth; TL: Tibia Length; R.s.: Mean square of residual

The independent variables which entered and stayed in the equation are indicated by an asterisk at cross-points with the dependent variable in question. The key for identification of the independent variables referred to by abbreviations in Table 3.12, 3.13, 3.15 and 3.16 are listed in Table 3.14.

TABLE 3.14 Abbreviations used in regression tables

Dependent Variables		Independent Variables	
Abb.	Variable Name	Abb.	Variable Name
H	Hand	W	Weight
FA	Forearm	S	Stature
UA	Upper Arm	SH	Sitting Height
FA-H	Forearm with Hand	BH	Bicondylar Diameter, Humerus
UA-FA	Upper Arm with Forearm	BF	Bicondylar Diameter, Femur
UL	Upper Limb	UG	Upper Arm Girth, Maximum
C	Calf	FG	Forearm Girth, Distal
T	Thigh	CAG	Calf Girth
		AG	Ankle Girth
		ULL	Total Upper Limb Length
		FL	Forearm Length
		FHL	Forearm with Hand Length
		HB	Hand Breadth
		TL	Tibia Length

The multiple regression equations are listed in Table 3.15 (for boys) and Table 3.16 (for girls). It is important to note, for the reason stated above, that the true values of the moment of inertia and the volume are the fifth and third powers of the values calculated from the equations. When using these equations to estimate the values of inertial characteristics, if the body weight appears in the relevant prediction equation, its cubic root should be used in calculation.

TABLE 3.15 Regression equations for inertial characteristics (Boys)

Dependent Variables	Equations
CG, H	66.447 - 2.857 × W + 0.02206 × UG + 0.02014 × ULL + 0.03595 × FL - 0.04433 × FHL
CG, FA	53.898 - 0.01315 × BH + 0.01554 × UG + 0.01734 × ULL
CG, FA -H	59.503 + 0.03419 × UG - 0.06253 × HB
CG, UA -FA	52.233 + 0.02706 × UG
CG, UL	57.395 - 0.09817 × BH + 0.04615 × UG
PMI, H	0.092 + 0.0002479 × S + 0.004471 × BH + 0.001203 × FG - 0.002193 × FL + 0.002395 × FHL
PMI, FA	0.1355 + 0.007311 × BH + 0.001364 × UG + 0.002638 × FHL
PMI, UA	-0.016 + 0.4544 × W + 0.001138 × ULL
PMI, FA -H	0.152 + 0.1293 × W + 0.007258 × BH + 0.0008225 × UG + 0.003288 × FHL
PMI, UA -FA	0.147 + 0.3543 × W + 0.001619 × UG + 0.002111 × ULL
PMI, UL	0.0709 + 0.4374 × W + 0.008420 × BH + 0.002223 × ULL
PMI, C	0.0234 + 0.01765 × BF + 0.003083 × TL
RG, FA	26.879 + 1.6199 × W + 0.1015 × BH - 0.02870 × UG - 0.04989 × HB
RG, UA	29.548 - 0.02002 × UG + 0.04879 × HB
RG, FA -H	25.075 - 0.009714 × UG + 0.03753 × HB
RG, UA -FA	28.853 + 0.002884 × SH - 0.01466 × UG
RG, UL	26.587 - 0.01804 × UG + 0.04248 × HB
RG, C	26.676 + 0.003111 × SH + 0.02963 × BF - 0.01173 × CAG
V, H	1.010 + 0.4749 × W + 0.03343 × BH - 0.006737 × FL + 0.008213 × FHL
V, FA	1.192 + 0.01155 × UG +0.01200 × FG + 0.007265 × FHL
V, UA	0.455 + 1.8973 × W + 0.01399 × UG
V, UL	1.309 + 1.4926 × W + 0.01539 × UG + 0.003637 × ULL
V, C	1.096 + 0.02375 × CAG + 0.01116 × TL

Abbrivations: H=Hand; FA=Forearm; UA=Upper Arm; FA-H=Forearm with Hand; UA-FA=Upper Arm with Forearm; UL=Upper Limb; C=Calf; T=Thigh;

W=Weight; S=Stature; SH=Sitting Height; BH=Bicondylar diameter, Humers; BF=Bicondylar diameter, Femur; UG=Upper arm Girth; FG=Forearm Girth; CAG=Calf Girth; AG=Ankle Girth; ULL=Total upper Limb Length; FL=Forearm Length; FHL=Forearm with Hand Length; HB=Hand Breadth; TL=Tibia Length;

TABLE 3.16 Regression equations for inertial characteristics (Girls)

Dependent Variables	Equations
CG, UA	54.11 + 0.02577 × S - 0.02537 × SH - 0.1059 × FL + 0.06504 × HB
CG, FA -H	60.01 - 0.009698 × SH - 0.04305 × UG
CG, UA -FA	54.61 + 0.03429 × UA - 0.04060 × FL + 0.05616 × HB
CG, UL	58.22 + 0.05039 × UG - 0.03321 × FL
CG, C	52.77 + 0.01973 × TL
PMI, H	0.0972 + 0.002269 × FG + 0.0009841 × ULL - 0.003931 × FL + 0.002330 × FHL + 0.002661 × HB
PMI, FA	-0.1476 + 0.005801 × FG + 0.005530 × FL
PMI, UA	0.1896 + 0.3158 × W + 0.001520 × ULL
PMI, FA -H	0.0107 + 0.1258 × W + 0.004511 × FG + 0.003602 × FHL
PMI, UA -FA	0.2201 + 0.3921 × W + 0.002339 × ULL
PMI, UL	0.2199 + 0.3723 × W + 0.0006424 × S + 0.002761 × FHL
PMI, C	-0.3592 + 0.001623 × S + 0.003446 × AG
RG, UA	29.57 - 0.02085 × UG - 0.02964 × FG
RG, FA -H	25.12 - 0.009151 × UG - 0.03342 × HB
RG, UA -FA	29.31 + 0.002516 × SH - 0.01572 × UG
RG, UL	27.48 - 0.01821 × UG + 0.02995 × HB
RG, C	24.28 - 0.01841 × CAG + 0.03894 × AG
V, H	0.7415 + 0.001658 × SH + 0.01333 × FG - 0.008455 × FL + 0.008990 × FHL + 0.007647 × HB
V, FA	0.6806 - 0.01008 × UG + 0.01973 × FG + 0.01138 × FL
V, UA	0.6844 + 1.334 × W + 0.01225 × UG + 0.003226 × ULL
V, UL	0.8730 + 0.9881 × W + 0.01204 × UG + 0.01511 × FG + 0.004770 × ULL
V, C	- 0.0096 + 0.003560 × SH + 0.01419 × CAG + 0.01206 × AG + 0.008030 × TL

Abbrivations: H=Hand; FA=Forearm; UA=Upper Arm; FA-H=Forearm with Hand; UA-FA=Upper Arm with Forearm; UL=Upper Limb; C=Calf; T=Thigh;

W=Weight; S=Stature; SH=Sitting Height; BH=Bicondylar diameter, Humers; BF=Bicondylar diameter, Femur; UG=Upper arm Girth; FG=Forearm Girth; CAG=Calf Girth; AG=Ankle Girth; ULL=Total upper Limb Length; FL=Forearm Length; FHL=Forearm with Hand Length; HB=Hand Breadth; TL=Tibia Length;

3.4 A DYNAMIC MODEL FOR THE LIMB SEGMENTS

Certain geometric solid could be used to model human body segments. These solids should preserve the mechanical properties of the limbs which they are modelling. One of the simplest model is a truncated cone (or, in terms of mathematics, a solid of revolution formed by a straight line, $y=(r_2-r_1)z+r_1$. The r_1 and r_2 here are referring to the same-name-parameters in Figure 1.2). However, a truncated cone has relatively larger radius of gyration, with the result that it cannot model a limb segment having small value of radius of gyration. The solid of revolution formed by a parabola $y=(r_2-r_1)\sqrt{z}+r_1$ (the coordinates are referring to Figure 1.2, r_1 and r_2 are the radii of the solid) has better property in presenting a limb segment.

As an example, Table 3.17 lists the parameters of the two models for limb segments of 10 years old boy. The parameter value for a full possible range of CG and RG are listed in Appendix II.

TABLE 3.17 Dynamic model of limb segments of 10 years old boys

Segment*	Parameters		$y=(r_2-r_1)z+r_1$		$y=(r_2-r_1)\sqrt{z}+r_1$	
	RG	CG	r_1	r_2	r_1	r_2
Hand	23.9	65.7	-	-	-	-
Forearm	28.9	57.9	0.1103	0.186	0.1074	0.225
Upper arm	30.7	55.7	0.1786	0.257	0.1662	0.278
Forearm with hand	26.5	61.6	-	-	0.0352	0.140
Upper arm with forearm	28.4	58.2	0.0787	0.130	0.0895	0.187
Upper limb	26.6	61.8	-	-	0.0352	0.138
Calf	27.9	59.8	0.0704	0.134	0.0739	0.202
Thigh	31.0	52.6	0.2099	0.252	0.2055	0.261

*Segments are in unit length.

3.5 COMPARISON WITH A PREVIOUS LIVERPOOL INVESTIGATION

In 1980, Dangerfield (personal communication) undertook an extensive anthropometric investigation in Liverpool area. With his permission, the current sample was compared with his data.

The mean value of each age group for each variable in the Liverpool data was calculated and then interpolated to obtain a mean value for each age point (as was done in 3.1.1). The maximum age of boys in the data was 12. As a result there are few age groups comparable for boys. Figure 3 shows the mean values for girls for ages 8 to 15 in both investigations. In the 12 variables which are displayed, all have the same mean value at age 8, except for the bicondylar diameter of humerus, in which the current sample has a smaller mean value throughout the age range. At the following ages, two patterns were found. The first is shown for weight, stature, and sitting height. For these variables, the mean values at ages 8 to 12 years are similar, and the two growth lines are coincidental. At ages 12 to 13 years, the current sample has exhibits a sharp increase in the mean value while the old sample maintains its rate of increase as for the preceding age step. As a result, the differences between the current sample mean and the old sample are shown. However, the difference between the mean values disappears due to rapid growth of children in the old sample at ages 13 and 14. The two samples exhibit the same mean values at ages 14 and 15.

The second pattern is exhibited by nearly all the other variables. For these variables, the current sample has higher average values at every age point, and the earlier adolescent growth spurt, as shown in the first pattern, can be identified for the majority of the variables. However, not all variables in the old sample displayed adolescent spurt.

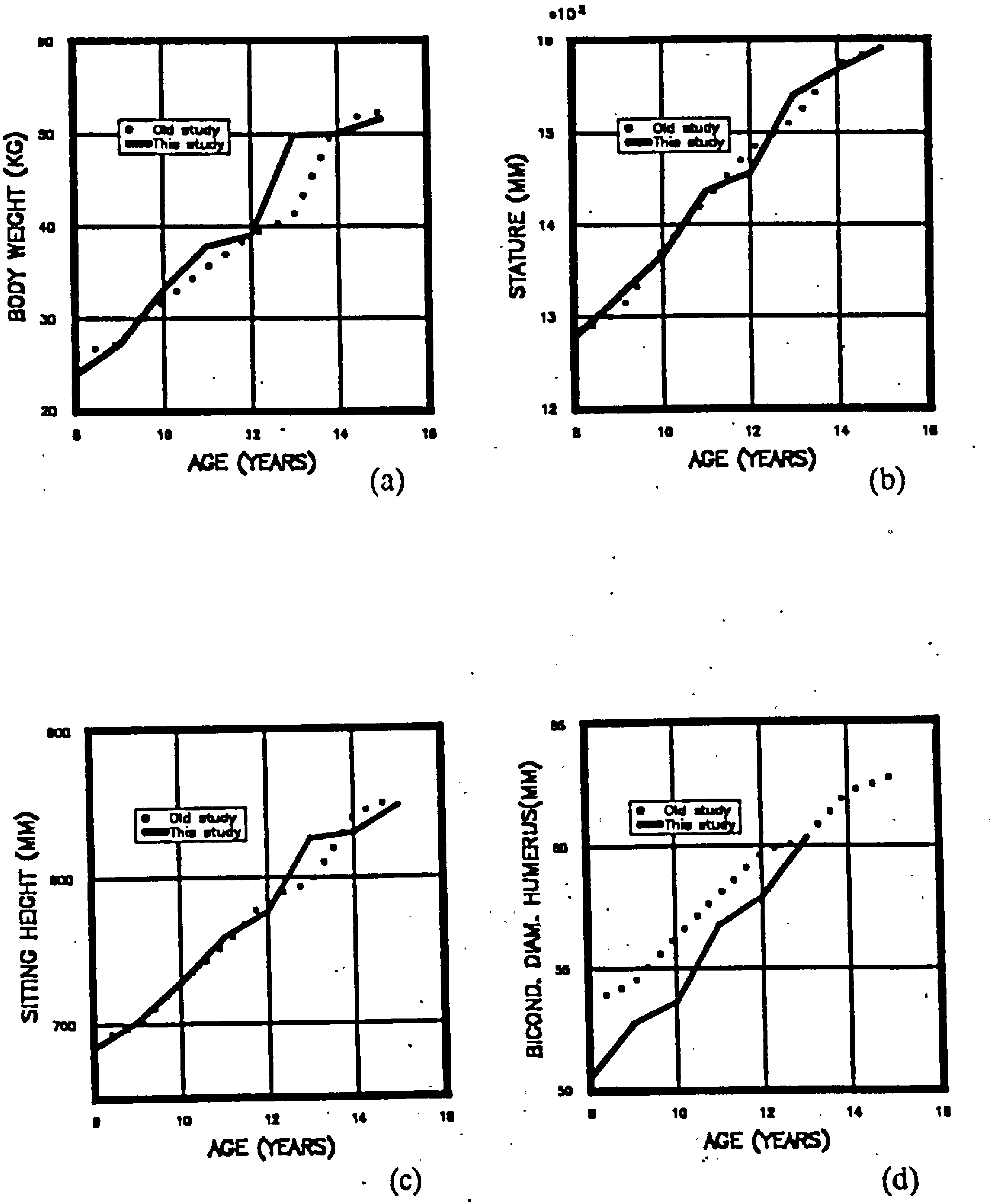


Fig. 3 Comparison of the results of this study with that of Dangerfield

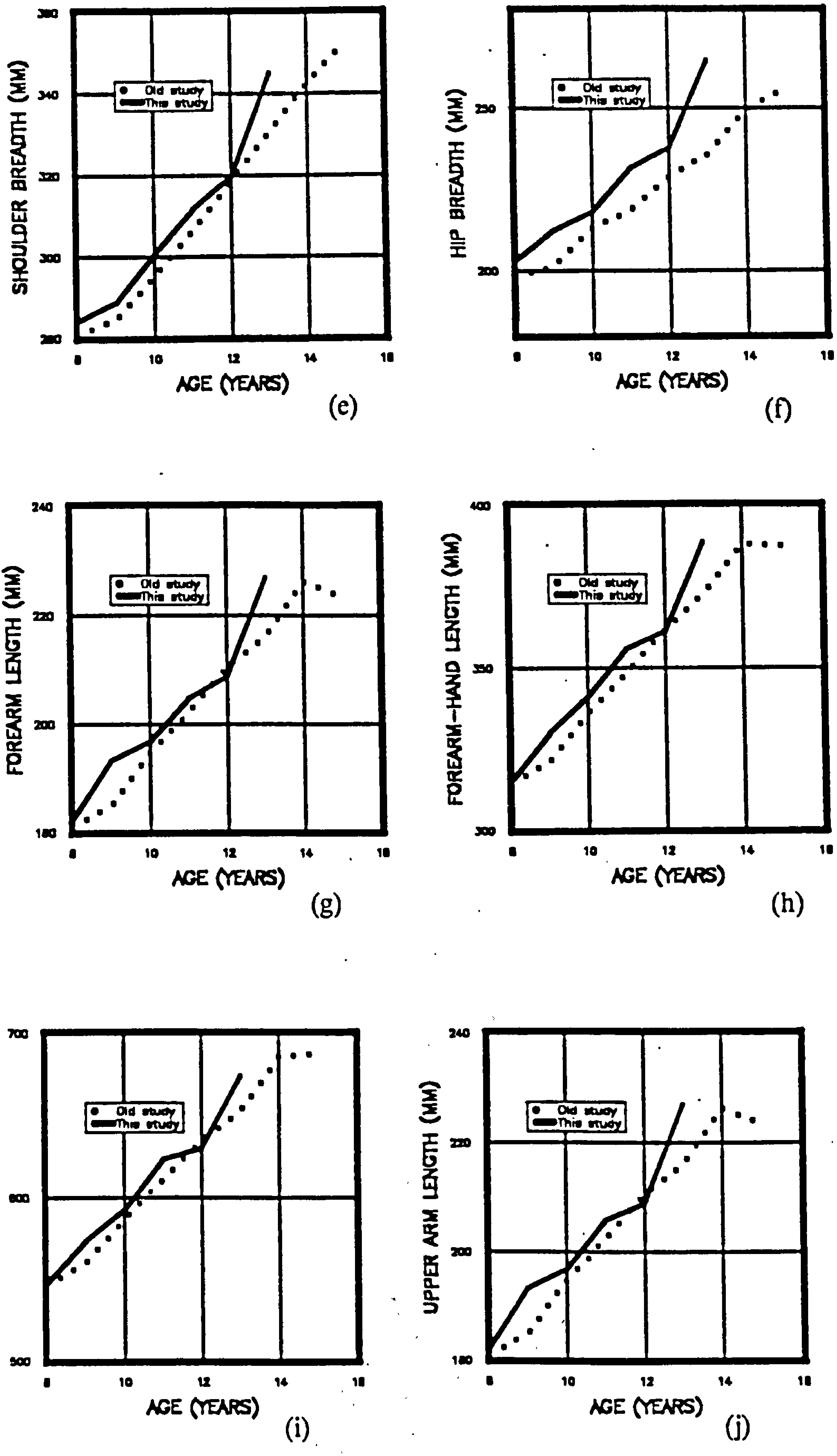
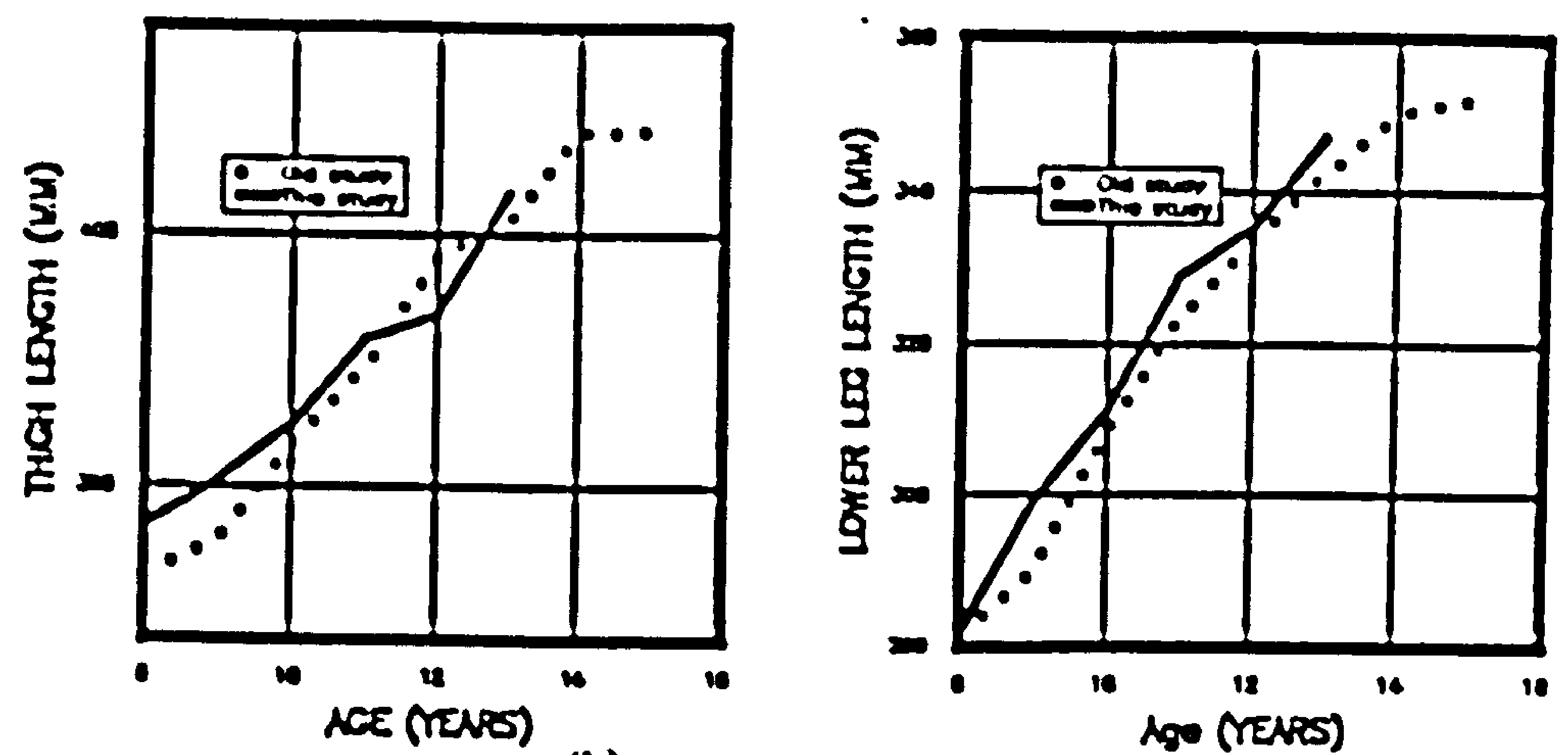


Fig. 3 Comparison of the results of this study with that of Dangerfield



(k) (l)

Fig. 3 Comparison of the results of this study with that of Dangerfield

4 DISCUSSION

4.1 METHOD

4.1.1 Sample size

Sample size is most rationally determined by the standard deviation of the variables selected with; if the means of two population are being compared, the critical limit for the possible difference between the two means should also be taken into account. The sample size is also subject to time, financial budget, technical error of the measurements, etc. If the measurements are composed of, say, conventional anthropometric variables, the sample size is generally decided on the variable which is most important, and which has the greatest standard deviation. In this case, stature is nearly always chosen to decide the sample size, and all the variable measurements are taken from all the subjects in the sample, so that a integrated data matrix can be obtained. But in other cases, if the measurements consist of two or more subgroups with very different properties, the above method often is not the best and may even be impractical. For example, in this study, the variables included both anthropometric and volume distribution measurements. The former are much more disperse in their distribution but the latter are time consuming to undertake. In this case, it is unnecessary for all the measurements to be taken on all the selected subjects to satisfy the accuracy requirements of the former; and furthermore, because the centre of gravity and the radius of gyration have a very small population standard deviation but relatively greater method error, it is illogical to waste time on their measurement. The sampling method adopted in this study therefore, is that the mass distribution measurements were undertaken only on a subsample, while the anthropometry was carried out on the whole sample. In fact, the two types of data were treated as two separate samples. Only in the analyses of correlation, allometry, and regression, are they linked logically with each other.

4.1.2 Data collection

The data in this thesis consisted of collected anthropometric variables and a series of data for limb mass distribution in living subjects. The anthropometric methods adopted are well-established and standardised. However, the limb mass distribution technique has not been previous published, although the principles underlying it have been adopted in a number of applications.

4.1.2.1 Water displacement method

Water displacement methods were used by Zook (1932) who collected the data relating to the volume of the body and body segments and by Drillis *et al* (1966) who located the position of the centres of gravity of living body segments. Although this method is both time consuming and considered not particularly accurate, it forms the standard method adopted in research studies in this field, and has been recommended by the relevant textbook (Winter, 1979; Miller *et al,* 1976).

However, the water displacement method is subject to a series of influence which may adversely affect the results of the measurement.

4.1.2.1.1 Design of the equipment

The structure of the apparatus used in this study has been described in 2.2.2.1.1. Particular attention has been paid in order for the design of the equipment to achieve best quality for the obtained data. In the apparatus as illustrated in Figure 2.2, if the tube C had been connected to cylinder A instead of B, the water would rise in cylinder A and tube B simultaneously; there would be very little time lag and this would have been a great advantage. But the disadvantage of that design is that because the cylinder must be quite thick to accommodate the limb being measured, a limb segment with length L would only lead to relatively little water rising in tube C, especially for a thin subject. As a result the accuracy would suffer.

The final design used in the study overcame this shortcoming. The diameter of the cylinder B and tube C are 7.6 cm and 3.1 cm respectively. The 2,000 ml of water displaced into B and C will produce a 36.5 cm rise in the water surface. However, because a few seconds are needed to allow the water in A to be displaced into B, resulting in the pen D not having a immediate full reaction to the limb movement. To overcome this problem, the board E is moved first a distance of approximately 1-1.5 cm, with a horizontal line drawn on the board. The subject then is asked to move down his/her limb slowly until the spring (J) linked with string I denotes the correct position. The subject is now asked to keep steady while the water overflows into cylinder B. A perpendicular straight line is drawn by the pen when the water level in the cylinder B goes up. Repeating this procedure, a step-like plot is obtained on the board. Provided the distances of each board movement are small enough, the dot set composed of the highest points of each perpendicular line can represent the accumulated volume, or, in the other words, the volume distribution curve of the limb.

4.1.2.1.2 Factors affecting accuracy

i) *Water temperature change:* Water has its greatest specific gravity (smallest volume for weight) at 4°C. Its volume therefore increases as the temperature rises or falls. If the temperature fluctuates markedly during the period of data collection, the volume of water displaced might be a measure of co-effects of both volume displacement and temperature changes. In normal indoor conditions, too much water would be displaced if the temperature rose, or *vice versa.*

ii) *Tremor of the subject:* It was found to be very difficult for some subjects to remain steady; this was especially true for young children. Their limbs often shake during the period of measurement with the result that the water was not evenly displaced gradually but 'thrown' out abruptly.

iii) *Sensitivity of the equipment:* The size of the water-supply container and the water-measuring cylinder affects the quality of the data. The water-supply container must have a large enough diameter to accommodate the limb, but if it is made too large, the adverse effect of surface tension will be magnified. Furthermore, the design of the cylinder used to measure the volume of displaced water affects the results directly. If the diameter of this cylinder is too large, the sensitivity, or precision of the equipment is low; if it is too small, an overlarge vertical water rising would result.

iv) *Water pressure:* Water pressure may cause minor deformation of an immersed limb. The deeper the limb is immersed in the water, the greater the pressure exerted on it by the water. For example, if the upper limb of a subject has length of 60 cm, the maximum pressure exerted on it at its distal end can be expressed as:

$$1\text{g/cm}^3 \times 60\text{ cm} = 60\text{g/cm}^2$$

However, this is only about twentieth of atmospheric pressure on sea level. It is therefore considered to be an unimportant error factor, even though a systematic error may be introduced from this factor.

4.1.2.1.3 *Estimated error of the methods*

It is considered that the main sources of the error in the practical measurements are tremor of the subject, and sensitivity of the equipment. Both of these factors might lead to random errors. The problem is that when they occur without being detected, how, or to what extent, may they affect the accuracy of the final results.

In this study, the displaced water was recorded as 'accumulated volume'. In mathematical terms, it is expressed as the body segment volume distribution function F(x), and not the density function of the distribution f(x). Here, $f(x) = dF(x)/dx$ (x is the length of the limb in the direction of main axis).

Suppose that, during the measurement of kth segment zone, there was a random error dv in volume measurement V_k, resulting from either too much, or too little water being displaced, it will most probably be compensated for in the next segment zone volume measurement V_{k+1}. Nevertheless, in V_{k+1}, a small random error independent of the error in V_k might be introduced as well. In this instance, a iteration method can prove that it does not affect the validity of the argument.

The mathematical formula used to calculate the centre of gravity from mass distribution data is as follows:

$$CG = \frac{\sum_{i=1}^{n} x_i M_i}{\sum_{i=1}^{n} M_i}$$

where, x_i is the distance from distal end of the body segment to the segment zone i with a volume V_i and mass M_i, $M_i = V_i \times$ specific gravity. The partial derivative of CG to mass M_j is

$$\frac{\partial CG}{\partial M_j} = \frac{x_j \sum M_i - \sum x_i M_i}{(\sum M_i)^2} = \frac{\partial CG}{\partial M_k} = \frac{x_k \sum M_i - \sum x_i M_i}{(\sum M_i)^2}$$

Suppose at segment zone j, a error dM_j is introduced into the reading. As stated above, at the segment zone j+1, it will be compensated for by $dM_{j+1} = -dM_j$. Thus the increase in CG is:

$$dCG = \frac{\partial CG}{\partial M_j} dM_j + \frac{\partial CG}{\partial M_k} dM_k$$

$$(k = j+1; \quad dM_k = -dM_j = -dM)$$

$$dCG = \frac{x_j\sum M_i - \sum x_i M_i - x_k\sum M_i + \sum x_i M_i}{\sum M_i} dM = \frac{x_j - x_k}{\sum M_i} dM$$

Say, for example, the distance between the two neighbour segment zones (X_{k+1}-X_k) is taken to be 30 mm, the volume of the limb (M_i) is 500 mm³, and the random error in the volume of segment zone j (dM_j) is 20 mm³ (practically this is very high). The error relating to the position of the centre of gravity will be: -30mm × 20mm³/500mm³ = -1.2mm. This is in reality insignificant. It is noticeable from this analysis that the point at which the random error takes place does not in practice make any difference to the result for the centre of gravity.

The increase of MI and CG resulting from random error cannot be expressed as succinctly as that of CG, due to the square function in their calculation. However, like in CG, the random errors in mass distribution data do not seriously affect their results.

4.1.2.2 Elliptical modelling technique

This method was used by Weinbach (1938), Jensen (1978), Yokoi (1985) and Ackland *et al* (1988) in studies of body segment inertial characteristics. It was adopted in this study only in collecting volume distribution data of thigh. The main advantage of this method is that it is easier to collect the data needed for the calculation. All dimensions required are linear so that this technique may be applied to segments on which other methods such as water displacement, cannot be used. The disadvantage is related to the lower quality of the final result. Errors may result from:

i) *Deviation of true cross-sectional shape from assumed elliptical shape:* The cross-sectional shape can change at each segment and also between individuals; none of the segments have a cross-section shaped exactly as an ellipse. An error in V_i is therefore unavoidable. However, the cross-sectional shape of the thigh is usually quite regular and fairly close to an ellipse. As a result, it is considered reasonable to assume that any resulting error will not be beyond reasonable tolerance.

ii) *The measurements of the three readings used to calculate M_i (maximum and minimum axis, and the distances between two sections):* The measurements can be undertaken either by direct body measurement or by photometry. The latter method is subject to additional error due to the deformation of the picture caused by photo-processing. Measuring the body directly is also a difficult process. Firstly, the anthropometric measurements used are nonstandard and secondly, since all the measurements are applied to pressure-deformative soft tissue, great care is needed in the data collection.

Unlike the water displacement method, the error of this technique is not easy to analyse mathematically. With this indirect technique, systematic errors are to be expected since the cross-section of the limb departs from elliptical shape in a non-random fashion. The errors resulting from the deviation of V_i are more serious for the moment of inertia than for centre of gravity, since the latter is not as sensitive to the errors in V_i as the former if the errors are in ratio.

4.2 STATISTICAL AND ALLOMETRIC ANALYSIS

4.2.1 Type I and Type II statistical errors

The objective of the selection of subjects for this research was to achieve, without distortion of the data, the largest variation for each anthropometric variable and to accurately determine the values of inertial characteristics. There were some practical difficulties encountered affecting the data collection in certain sex-age groups, common to any anthropometric survey. This problem arises when the data set is subdivided into age groups in order to compare the mean values for each variable between boys and girls. The result was a small number of observations in some age categories. Consequently in these categories the null hypothesis often cannot be rejected when a test has been carried out. In this instance, care is needed to avoid a type II statistical error.

Even if a preliminary statistical test suggests that the null hypothesis cannot be rejected, this is not necessarily the end of the matter. Snedecor pointed out that “a test of significance is sometimes thought to be an automatic rule for making a decision either to 'accept' or 'reject' a null hypothesis. This attitude should be avoided ... The size of the sample from which the test of significance is calculated is also important. With a small sample, the test is likely to produce a significant result only if the null hypothesis is very badly wrong" (Snedecor *et al,* 1978. p28). In practice, the critical probability of 0.05 is most often used to judge a result. When $p=0.05$, the null hypothesis can be rejected with 95% confidence; the probability of type I error (the null hypothesis is true but is rejected) is 5%. If the test results show $p=0.1$, it is not so certain to reject the null hypothesis because the risk of type I error is now 10%. However, on the other hand, it is not certain that the situation stated by the null hypothesis is true for, there is still 90% confidence of rejecting the null hypothesis. General statistical theory does not provide a method to measure the probability for type II statistical error (the hypothesis is wrong but is accepted), but when the samples are small, this probability would be high. It is easily seen in the formula used to compute the 't' value, the criterion applied to judge the difference in two means. When the means and variances (two parameters representing the nature of the population) of the two samples remain unchanged, 't' is determined by the number of observations. The conclusions of this review are the reason why in Table 3.4, significance levels at $p=0.05$, and also $p=0.10$ and $p=0.20$ are included.

4.2.2 Correction of the means based on age

When comparison between the mean values in each age group for each sex is made, it is obvious that the means as shown in Table 3.2 are not valid. This is because in this project, the age group n is defined as the set of the individuals aged from n minus 0.500 to n plus 0.499. For example, an individual aged 10.500 is classified into age group 11, or another aged 12.499 is treated as age 12. So, when an age group is mentioned, the 'age' is the theoretical mid point of the group. But in a real sample, this age is, generally speaking, neither the mid point nor the mean of the individuals in the group. The difficulty arises from the fact that the two sex groups which have the same age limits and are defined as the same age group, usually have different average ages, particularly if the sample sizes are small. Attention has to be paid to this phenomenon. The negative test result applied to the difference in the mean value of age cannot prove the validity of the comparisons of other variables simply because that for the sample itself the sample is no longer a 'sample', but a population. For example, it is meaningless to say that in a certain age group, the female has a bigger average value in a certain variable than male if the female is also in average two months older than male. This is especially important in age categorise that include adolescence.

In order to compare the variable means between the two age groups in the case stated above, the ages must be standardised. Between the two most important parameters describing variable distribution (mean and standard deviation), the sample mean undergoes change for most variables throughout entire growth period; in fact, 'growth' is defined on this parameter.

Conversely, standard deviation is usually stable and may be assumed to be equal in different sexes and ages. In fact, the assumption of equal variation forms the basis for any test of sample mean, including either Student's 't' test, or the analysis of variance. A detailed analysis might show a existence of the difference in the standard deviation. In theory, the larger standard deviation should occur during adolescence because of reduced synchronism of growth among individuals. This problem is beyond the result of this study.

A data interpolation technique, known as the cubic spline function method, has been applied in order to estimate mean values at standard points. The principle of this method is to determine a series of cubic functions in order to construct a curve which pass smoothly through every datum point. Additionally, this curve has the property that it has first and second rank derivatives, which are continuous except at the datum points (knots) for the second derivative. For example, for $n+1$ datum points named d_0, d_1, ..., d_n with coordinates (x_0, y_0), (x_1, y_1), ..., (x_n, y_n), n cubic functions f_0, f_1, ..., f_{n-1} can be selected, which link with each other at the datum points d_0, d_1, ..., d_n. At d_i $(0<i<n-1)$, the conditions of $f_{i-1}(x_i)=f_i(x_i)$, $f'_{i-1}(x_i)=f'_i(x_i)$, are satisfied. Thus a continuous function through all known datum points has been created so that for any points x, in the entire interval $[x_0, x_n]$, the corresponding position, d, can be interpolated with reference to the known data. For instance, in Table 3.2.8, the boys' average stature at age 8.36, 9.01, 9.93, 11.04, 12.04, 13.02, 13.97, 15.05, and 15.94 are known to be 1300.8, 1320.4, 1371.8, 1428.2, 1497.6, 1530.1, 1605.5, 1657.3, and 1717.6. Eight piecewise cubic functions $Y_i=a_i+b_i(x-x_i)+c_i(x-x_i)^2+d_i(x-x_i)^3$ $(i=0,7)$ can be obtained. If the average stature at age 10.00 is required

(because $x_2 = 9.93 < 10.00 < 11.04 = x_3$, and a_2, b_2, c_2, d_2 are 1371.8, 53.380, -18.507, 14.558 respectively), it can be calculated using the formula:

$$\text{Stature}_{10} = 1371.8 + 33.38(10-9.93) - 18.51(10-9.93)^2 + 14.558(10-9.93)^3$$

The mean stature for the ten year-old boys is estimated as 1375.2 mm, 3.3 mm higher than the sample mean at 9.93 years, when the stature is 1371.8 mm.

A FORTRAN 77 programme (Appendix V) was written by the author to carry out the procedure described above. The estimated values of the mean for each variable at standard age points were used for the comparison between sexes of means in each age group.

4.2.3 Comparison of means among age groups

It is meaningless to test significance of the difference in mean value of anthropometric variables among age groups. For example, no matter what the result of the test is, the mean statures of boys aged 9, 10, and 11 years in a human population are impossible to be the same, though in the statistical procedure the probability for the null hypothesis not to be rejected does exist.

From the above argument, it is apparent that the test of significance for the mean value of the groups divided by the age is not necessary, except for special purposes. In this chapter, only the analysis of variance for variables 1) which are dimensionless (pure shape variables), and 2) which have different growth patterns between girls and boys are discussed.

4.2.4 Correlation and allometry

The linear correlation of two variables is a method used to reveal whether two variables are affected by each other and to reveal the direction and strength of the relationship, which is expressed by the sign and the value of the correlation coefficient.

Allometry has wide applications in different fields. Gould (1966) defined it as 'the dependence of shape variables upon size variables'. In this thesis, allometry is the assumption that during the growth children change the ratios in their constituent body parts, due to their demonstrating different growth velocities. In practice, this assumption is more often applied to a whole population rather than to a individual, by using the 'age' scale to replace the 'time' scale in the measurement of degree of growth, and introducing statistical method into the operation. The alternative of allometry is isometry, whereby the 'body', either as an individual or a population, retains a geometric similarity throughout a period of time. Huxley (1924) suggested a practical formula to describe allometry, This form has been adopted in most research programmes. Huxley's formula is:

$$Y=AX^k$$

where Y is the 'shape' variable and 'X' the size variable, whilst A and k are constants.

4.2.4.1 *Size, shape, and size-correlated variables*

In the formula $Y=AX^k$ that Y defines shape is not scientifically true, since shape cannot be expressed by a variable possessing a dimension. The variables usually used as Y in the formula are not solely shape alone; only their interaction with X causes them to be 'shape'. Furthermore, in instances where the size variable is unavailable, the sum, or geometric mean, of these 'shape' variables may be used as size (Hills and Wood, 1984). However, geometrically speaking, shape is logically independent of size. This fact is another evidence against these variables being 'shape'. In order to distinguish those variables from size as well as from 'pure' shape variables (indices), they have been defined as size-correlated variable in this study.

4.2.4.2 *Nature of Huxley's equation*

If a logarithmic transformation is performed on both sides of Huxley's equation, the formula becomes:

$$\ln Y=\ln A+k\ln X \quad \text{or}$$

$$y = a + kx$$

this is the linear expression of allometry (note that this is a regression line, not an algebraic equation). Reconsideration of the original equation in exponential form

$$Y = AX^k$$

$$\frac{dY}{dX} = kAX^{k-1}$$

it shows that when $k > 1$, Y has more increase than X, if $k < 1$, the reverse is true. If $k = 1$ and the dimensions of Y and X are same, then Y shows a linear increase with X. This is a special case of allometry, called isometry, in which the subject does not change its shape with regard to the change in size X, but maintains a geometric similarity. Generally isometry is the case when k has the value equal to the power of Y over that of X; this is termed the 'dimension coefficient k_0 in this thesis. For example, if Y is a volume with dimension L^3, and X is length with dimension L^1, $k_0 = 3/1 = 3$ shows the isometry of volume on length. The expression becomes clearer if it is discussed alongside that of velocity. Suppose t is time, then dY/dt and dX/dt are the velocities of the growth of Y and X. From the formula:

$$\ln Y = \ln A + k \ln X$$

calculating the derivatives on t for both sides of the equation, we have

$$\frac{1}{Y}\frac{dY}{dt}=\frac{k}{X}\frac{dX}{dt}$$

or

$$\frac{(\frac{dY}{dt})}{(\frac{dX}{dt})}=k\frac{Y}{X}$$

now, if $k = k_0$, the ratio of the increase of Y and X in a time interval dt is the same as their dimension coefficient, indicating absence of shape change. If $k > k_0$, ($k = k'k_0$, $k' > 1$), then Y has more relative growth, and *vice versa*. The bigger the difference between k′ and 1, the greater the change in shape.

The above discussions used the ratio of Y/X as the measurement of pure shape. It made clear that in the application of this model, Y must be a variable possessing a geometric dimension, but not a ratio, or any dimensionless measurement, for example, an angle. In terms of the relationship of shape with size, the dimensionless variables differ from size correlated variables. If there is any linear correlation between dimensionless variable with size, the fact that shape changes with size is suggested, no matter what the relationship is. Size correlated variables do not have this property; if they are correlated with size in the way of $k = k_0$ in the allometry model, as discussed above, they possess no shape change.

As discussed earlier, dimensionless variables are usually 'pure' shape variables which are affected by changes of body overall size not in a geometric way, ie. there is no a geometrically logical relationship between them and body size. If any statistical relation is found, it is due to 'internal', biological, reasons, However, there has been much discussion concerning the use of ratios (Atchley *et al,* 1976), and this will be discussed later.

4.2.4.3 Regression as an expression of allometry

In the allometry equation $Y=AX^k$, k, the allometry coefficient, determines the geometric relationship of Y and X. In logarithmic transform, $y=a+kx$, k is the slope of the regression line. In cases where the data are logged, the regression coefficient corresponds to the allometry coefficient in the original form. This provides a practical way of estimating the value of the allometry coefficient by use of regression method.

4.2.4.3.1 Least squares regression

In practice, the regression slope may be defined in different ways, depending on different principles (Ricker, 1973). In statistics textbooks, the most common model is the least squares method. This minimises the sum of the squares of the distances from the points to the regression line in the direction of dependent variable. It has the advantage of making it easier to estimate the standard error of the dependent variable so that this method is suitable for prediction purposes.

From the definition of the regression slope:

$$b_{yx} = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2 / n}$$

it can be deduced that

$$b_{xy} b_{yx} = r^2$$

here, r is the correlation coefficient. Compare this with the well known analytic geometric formula:

$$k_{yx} k_{xy} = 1$$

it is obvious that the smaller the absolute value of the correlation coefficient, the more the least squares regression slopes affect the geometric relationship of Y and X. In a bivariate Cartesian coordinate system, the data points form a correlation ellipse. Thus, the regression line which best expresses the property of the ellipse should pass though the long axis (major axis) regardless the eccentricity. The disadvantage of least squares method lies with the fact that the slope changes with eccentricity, even though the major axis of the correlation ellipse does not change. Here, if the major axis is neither horizontal nor vertical, the eccentricity is a parameter similar to the absolute value of the correlation coefficient (If $r=0$, datum points form a circle, and the eccentricity of the correlation ellipse equals to zero as well. In contrast, if $|r| = 1$, datum points form a straight line, and the correlation ellipse has eccentricity = 1).

4.2.4.3.2 Major axis regression

The major axis regression, with slope z, minimises the sum of the distance from each datum point to the supposed regression line. It passed through the major axis of the correlation ellipse of X and Y, so that it best reflects the functional relationship of the two variables. The major axis slope z could be calculated as:

$$z = \tan\left(\frac{1}{2} arctg \frac{2\sum xy}{\sum x^2 - \sum y^2}\right)$$

The major disadvantage for the major axis slope lies with the fact that its value is affected by the scales of the two variables in a non-linear way. For example, when the unit of Y is millimetres, the slope is not ten times that when the unit is centimetres. For this reason, the slope becomes meaningless if the dimensions of the two variables are not the same.

Sokal (1981) gave a practical way to compute major axis z, and its confidence limits, L_1 and L_2. However, it should be noted that the trigonometric formulas produced to calculate L_1 and L_2 (p. 597) are incorrect:

$$(L_1, L_2) = tan[arctan(b1) \mp \frac{1}{2} arcsin(2\sqrt{H})]$$

They should be shaped:

$$(L_1, L_2) = tan[arctan(b1) \mp arcsin\sqrt{H}]$$

where b1 is the major axis slope; in this thesis it is expressed as z.

4.2.4.3.3 Reduced major axis regression

Teissier (1948) derived the reduced major axis regression (also called geometric mean regression). The principle of this method is to minimise the sum of the products of the vertical and horizontal distances of each datum point from the regression line. Note that in the least squares method, only vertical distance was considered.

Suppose the reduced major axis line is y=v+kx, the sum of products of the two distances from the line to datum point (x_i, y_y), D, is given by:

$$D = \sum[(vx_i + a - y_i)(\frac{y_i - a}{v} - x_i)]$$

If the partial derivatives of D, $\partial D/\partial v$ and $\partial D/\partial a$ are calculated and returned to zero, when D has its minimum value, the following results are achieved:

$$v^2 = \sum(y_i - a)^2 / \sum x_i^2, \qquad a = y - vx.$$

If the data are centralised, then,

$$v^2 = \sum y_i^2 / \sum x_i^2$$

It has the relationship with the least square regression slope b:

$v = b/r$, where r is the correlation coefficient, and

$v_{xy} = b_{xy}/b_{yx}$, $v_{xy}v_{yx} = 1$

4.2.4.3.4 *Comparison of the three regression slopes*

Ricker (1973) presented a detailed discussion of different regression methods. Four important points with practical usefulness were raised in this thesis. They are:

1) The least squares slope, b, compromises the geometrical correlations of Y with X, especially when the correlation coefficient is not high. Therefore, it is not a good method for estimation of the allometric coefficient.

2) Major axis slope, z, can express the correlation of variables X and Y without bias. But it is only meaningful when the dimensions of X and Y are identical.

3) Like the major axis slope, the reduced major axis slope, v, has the relationship $v_{xy}v_{yx} = 1$; and like the least squares slope, v changes linearly with the changes in either X or Y. Compared with z, v is conservative to one: it always positioned between z and one:

$1 < v \leq z$ (if $z > 1$)

$1 > v \geq z$ (if $z < 1$)

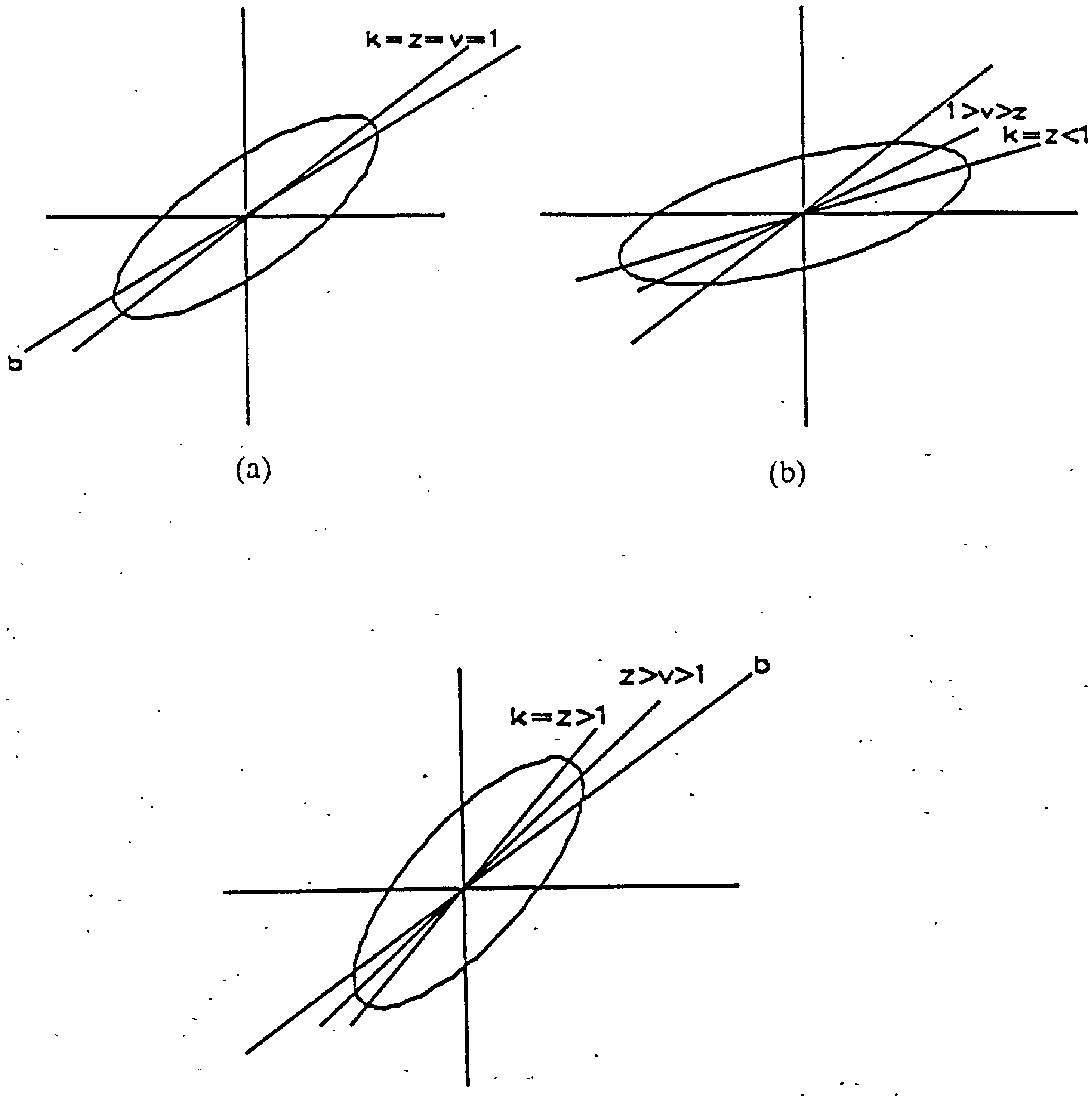
$v = z$ (if $z = 1$ or $r = 1$)

4) From the relationship $v = b/r$, it is known that b is always smaller than v. When $z = k = 1$, there is:

$$b < v < z = k$$

This means that b gives an even worse estimate of the allometric coefficient when $k > 1$.

The relationship of these three slopes is illustrated in Figure 4.1.



(a) (b)

(c)

k: Major aixs of an ellipse; z: Major aixs slope, an un-biased estimation of k in a correlation ellipse; v: Reduced major axis; b: Least square regression slope

Fig. 4.1 Relationship of three types of slope

4.2.5 Use of ratios

There has been much discussion and debate on the use of ratios in the study of growth. Atchley *et al* (1976) pointed out that ratios were usually skewed to the right and leptokurtic, especially when the coefficient of variation of the denominator is larger. Thus a spurious correlation between a derived ratio with its component variables is produced. Because of these problems, Atchley and his co-works argued that the use of ratios should be avoided in growth studies. However, Atchley's views have elicited criticism from many scientists. Atchley's paper (1976) was based on a computer-generalised data set, in which the variables were independent of each other. This is unlikely to occur in the biological data.

Hills (1978) pointed out that the properties of ratios are not so bad that they should prevent ratios from being used; in particular, if the data are logged, the disadvantages of ratios would be reduced. Dodson (1978) claimed that ratios were useful in growth studies. He found that the coefficient of variation of ratio data is a linear function of the absolute value of the difference between the allometric coefficient and one, which represents isometry. Furthermore, the loading of the first principal component of ratio data is negatively correlated with the allometry coefficient. Dodson also found that in principal component analysis, ratio data may give better results than original data.

From the equation (in 4.2.4.2)

$$\frac{\left(\frac{dY}{dt}\right)}{\left(\frac{dX}{dt}\right)} = k\frac{Y}{X}$$

it is clear that the definition of Huxley's allometry model is in fact the relationship of the ratio of growth speed of two variables and the ratio of their current status. Suppose during a time interval from t_0 to t_1, the variables X and Y changed from X_0 Y_0, to X_1, Y_1. Allometry is indicated by $Y_1/X_1 \neq Y_0/X_0$ (or $Y_1/X_1 \neq k_0Y_0/X_0$, if the dimensions of Y and X are not the same). In fact, t could not only be time, but also any other continuous variables. Practically, gene change can be treated as continuous, so that comparisons of ratios between populations is possible, and meaningful.

A few ratios are used in this thesis as pure shape variables (the centre of gravity and the radius of gyration are expressed as a ratio in this thesis, as in most previous studies). However, attention has been paid to avoid possible mistakes resulting from their peculiar statistical properties.

4.2.6 Use of somatotype distance parameters

In handling the somatotype data, there has been speculation among researchers that the three components of somatotype should be considered all together by deriving a new parameter. As a result, Ross *et al* (1973) suggested that the Somatotype Dispersion Distance (SDD) could be used to measure the dissimilarity of two somatotypes. The SDD is calculated not from data of the three components of somatotype, but from a two dimensional somatoplot, to yield a scalar quantitative (distance) value. The larger the SDD, the more different are the two compared somatotypes.

However, Ross's method was criticised by Duquet and Hebbelinck (1977). They stated: "There is, however, a distinct difference between a somatotype and its projected value or somatoplot. In our opinion, the use of somatoplot distances may lead to a distorted view of somatotype relationships, and cause false deductions." Duquet *et al* highlighted a possible error in Ross's thinking. In fact, in terms of the methodology, the somatoplot is a method of displaying three-dimensional somatotype data in a two-dimension plane, which makes visualisation easier. The cost is of losing information, as in principal component analysis (PCA). It seems pointless for one to visualise the data first and then quantify them again, as Ross suggested.

Duquet *et al* suggested a formula to calculate the Somatotype Attitudinal Distance (SAD) of two somatotypes in somatotype space. This method is theoretically much better than that of Ross. Appendix VI in this thesis gives the SAD values of paried group means. However, there are still statistical properties which require further consideration. From the formula:

$$SAD_{A,B} = \sqrt{\sum_{i=I}^{III} D_{i,}(A,B)}$$

it can be considered that the SAD is a special case of widely adopted distance analysis, when the three variables are three components of somatotype. Distance analysis is a classification technique. When the formula is used, an orthogonal coordinate system is implied (ie. the components are independent each other). However, the somatotype does not have this property. This can be demonstrated by the results in this thesis (see Tables 3.5 and 3.6). Here, both endomorphy and mesomorphy are correlated with ectomorphy ($|r| > 0.5$). In this case, the Mahalanobis distance is usually suggested (Chatfield and Collins, 1980), in which the covariance of the components is taken into account.

It is also important to consider, although both Ross *et al* and Duquet *et al* ignored it, that the somatotype components are usually derived from ten anthropometric variables (Carter, 1972). Inasmuch as the SDD distorts somatotype relation, due to its reduced dimension, as Duquet *et al* noticed, it is also questionable that the SAD creates a similar problem.

Carter, Ross, Duquet, and Aubry (1983) gave an introduction to the use of SAD and related parameters. However, in terms of mathematics, this paper was not well presented. Considering the unknown properties of the SDD and SAD, the author of this thesis believes that caution should be applied to their use, especially in the case of the SDD, which requests more work to calculate, and yields less information.

4.3 RESULTS AND COMPARISONS

4.3.1 Anthropometric variables

It is believed by some investigators that there is little difference in the means of anthropometric variables until the onset of adolescent spurt (Snyder *et al,* 1977). This is not so. Table 3.3 and 3.4 showed that the differences exist in a number of variables. As explained in 3.1.2, one, two, or three arrows in a cell in table 3.4 indicated significance levels of $p=0.2$, 0.1, and 0.05. If there is only a single cell with one or two arrows in a row, it should be treated as a random appearance. If there are three-arrow-cells in a row, substantial differences in the mean between the sexes is suggested. Table 3.4 shows that even with a small sample as in this study, the differences in mean value between the sexes could be found both before and after the onset of adolescence.

In the three somatotype variables, endomorphy behaved differently from mesomorphy and ectomorphy. Generally speaking, girls have a higher value for endomorphy than boys while boys have greater mesomorphy and ectomorphy values. In fact, these three variables correlate with each other. Table 3.3 and 3.4 shows, that for mesomorphy, boys only achieve a significant mean difference against girls at the age of 9 years ($p<0.01$). At age 12 and 13, no substantial difference can be detected. In contrast, for ectomorphy, the differences exist in the older age groups. The author believes that this is due to the earlier onset of adolescence of girls diminishing the difference. For ectomorphy, the higher value for the boys can only be detected after the onset of their pubertal growth spurt. The results for weight and stature add support to this view: at age 13, when girls have already passed their peak growth velocity, but boys have just commenced these, girls show their great advantage in weight ($p < 0.02$) but fail to show this advantage in stature. In contrast, at age 15 years, boys have much higher value for stature ($p < 0.02$), but not for weight.

Mesomorphy displays significant age changes in boys ($F = 10.0$, $p < 0.001$). Detailed analysis shows that from age 8 to 13 years, this variable remains stable. However, from age 13, its values decrease monotonically (an especially rapid decrease occurs between age 13 and 14 years). The author believes that this is due to the rapid stature increase which is not matched by the growth of muscles and bones during this period. This decrease in mesomorphy has not been observed in girls. However, there is a significant age-related difference in ectomorphy for girls ($F = 2.7$, $p < 0.01$), which are not present for boys. Older girls have lower values for ectomorphy than younger girls, indicating that they become fatter during the growth period. This result agrees with that observed in allometry, where girls' weight shows positive allometry against stature. This trend becomes more significant in the girls after the age of onset of their adolescent growth spurt (Table 3.8).

Girls have a rapid increase in sitting height from age 12 to 13 years, resulting in a significant difference in mean between the sexes at age 13. They then grow little in the following years. The sharp change in sitting height is also seen in boys, but at age 14 and 15 years. This observation agrees with the data of Shuttleworth (1939) quoted by Tanner (1962, p. 44). In terms of the ratio of sitting height/stature, girls maintain a steady value (about 53%) throughout the age range, showing little change with age ($F=1.3$, $p>0.05$). However, a large change occurs in the ratio for boys ($f=11.0$, $p<0.001$). As stated in 3.1.3.4, boys reduce this ratio value until 14 years old and then show a little recovery. This result was also observed by Hansman (1970). Hansman's results were illustrated by Malina, who stated "the ratio for boys and girls is essentially identical until about 11 years of age, when it becomes slightly higher in girls and remains so throughout adolescence into adulthood" (Malina, 1974, p. 120). As a result, at and after age 13 years, girls have a higher sitting height/stature value; in the other words, they have relatively shorter legs than boys.

The relationship of sitting height with ectomorphy is very different between the sexes. In boys, sitting height is found to be independent of ectomorphy ($r=-0.04$), whilst in girls, the correlation coefficient is -0.308 ($p<0.01$), suggesting a weak negative relationship (Table 3.5, 3.6). In contrast, the ratio of sitting height/stature is negatively correlated with stature in boys ($r=-0.46$, $p<0.01$), but not in girls ($r=0$). Both of these correlations are between two variables in which one has dimension and the other not. As discussed in 4.2.4.2, it is suggested that shape changes with size if the correlation is significant. For boys, sitting height is independent of shape, or body composition, but the ratio of sitting height/stature is affected by the value of stature and body weight. Because the partial correlation coefficient between body weight and sitting height ratio (assuming stature to be constant) is very small, the effect of weight is negligible. The partial correlation coefficients $r_{\text{(weight,sitting height) (stature)}}$ for boys is 0.223, for girls is 0.331; the partial correlation coefficient $r._{\text{(stature, sitting height) (weight)}}$ is 0.694 for boys and 0.816 for girls. In girls, the correlation between sitting height and ectomorphy indicates that leaner girls are more likely to have longer legs, although relative leg length appears to have little relationship with stature. In contrast, relative leg length is related to stature in boys.

Another observation should be noted. The zero correlation of the sitting height ratio with stature suggests that it is not necessary for a ratio to make a spurious correlation with its denominator, as Atchley *et al* (1976, 1978) claimed. The conditions required for X and X/Y not to make a spurious correlation is not going to be discussed in this thesis. However, the high correlation between X and Y is nevertheless an important condition, though not the only one. Notice that the correlation between sitting height (X) and stature (Y) is higher in girls than in boys, but that the zero correlation in sitting height ratio (X/Y) with stature (Y) takes place in girls.

Allometric analysis confirmed the results concluded from variance analysis. If stature is used as the overall body size variable, on average, boys have a negative sitting height allometry whereas girls have positive allometry. However, detailed examination of the results indicated that after the onset of adolescence boys display a positive allometry while younger girls in fact have isometry. Variance analysis did not show the fact that older girls have very high growth velocity for sitting height in relation to stature, which is shown in the analysis of allometry ($z = 1.22$, 95 per cent confident limit ranges from 1.10 to 1.36, these values are higher than those in any other subgroup,

Table 3.10). This result means that at the age stage after the onset of adolescence (or at least, a short period within this stage), tall girls tend to have an even higher relative value for sitting height. The reason why variance analysis failed to demonstrate this is that the individuals are grouped by age in variance analysis, whereas the higher sitting height is companied by higher stature, but not higher age.

Few linear measurements have shown boys to have significantly higher means over girls in the lower part of the age range in this sample. The only exception to this are found for the two bicondylar diameters: ie. humerus and femur. In these two variables, boys have higher average values than girls throughout the age range, with a significant level for the femur of $p < 0.05$ at ages 9, 10 and 12 years old. Additionally, for both variables at age 8, and for the humerus alone at age 12, boys have higher value than girls, but at a lower significance level ($p < 0.1$). This indicates that even before adolescence, boys have thicker limb bones. Correlation analysis shows that there are similar high, positive, relationships of these variables with body weight and stature in both sexes. However, the relationship with their quotient, ectomorphy, differs between sexes. The correlation coefficients are much lower in boys than in girls, even though they all show significant, negative correlation (Table 3.5, 3.6). This suggests that the bicondylar diameters are less affected by the factors of leanness-fatness in boys. In contrast, in girls, they are strongly affected.

It is interesting to examine the allometric relationships between these two bicondylar diameters and the size variables. If stature is used as the size variable, all subgroups (younger boys, older boys, younger girls, and older girls) display positive allometry for both diameters. If weight (or strictly speaking, the cubic root of weight) is used as the size variable, positive allometry is only seen in older boys; the younger boys and both groups of girls have negative allometry. In terms of biomechanics, if the bones are 'designed' to resist the compressional stresses resulting from gravity, these two bicondylar diameters, which represent the strength of the bones, should have an allometric relationship with the cubic root of body weight, with an exponent 1.5. The results suggest that the rate of developing compression stress-resistance ability is not as high as the speed of the stress increase (ie. k less than 1.5), so the ability to resist compressional stress must be an advantage set against the increase of body weight. On the other hand, these two diameters have a positive allometry against stature. Comparing these results against geometric similarity, elastic similarity, and constant stress models (McMahon, 1984), shows they are closer to a geometrical similarity model (or between it and an elastic similarity model if stature is used as body size).

An important phenomenon is noted here. For the bicondylar diameter of femur, the allometric coefficient against stature is 0.83 in boys. However, in the subgroups of boys, before and after the onset of adolescence, the coefficient is 1.09 and 1.31 respectively; both values are greater than 0.83. This phenomenon might occur when the slopes in the two subgroups differ substantially. Care must be taken to avoid a misleading result. It suggested that it is a good practice (and maybe essential) to analyse allometric coefficients piece by piece whenever a growth study is undertaken.

Hansman's (1970) data suggested that boys and girls shared the same value of shoulder breadth up to the age of 14 years, after which boys continue to growth with a high velocity whereas girls have little subsequent increase. His data also showed that girls have a higher average value for hip breadth until the age of 16 years old when boys catch up. Both of these observations are confirmed by the present study, except that the information relating to the growth status of girls older than age 14 years for some anthropometric variables was not available for this study. The explanation for these missing data is that it was particularly difficult for the author to obtain the necessary permission to take measurements from female subjects at this age range.

The index of hip breadth/ shoulder breadth showed a higher average value in girls in all age groups. The value of this index for both sexes was observed to increase with age, suggesting that hips became relatively wider. However, it is not obviously so. At the age of 16 for boys and 14 for girls, a sharp decrease in the values was found. Unique for this index is the finding that the standard deviation in both sexes became greater with age. This nevertheless reflects that the difference between individuals is sufficiently manifest in the older age groups; the 'F' tests were not valid for this index.

Girls differ from boys in the way that linear variables continued to correlate with ectomorphy. For majority of the length and breadth variables in boys there was no significant relationship with ectomorphy. This was reversed for girls, where a negative correlation was found to exist for most variables with ectomorphy. Firstly, this observation reflects the fact that girls are subject to more shape changes during the growth period. Secondly, if allometry is taken into account, these effects are rather more predictable. As body weight display more positive allometry in girls ($k=1.31$), ectomorphy would have the dimension $L/L^{1.31}=L^{-0.31}$ for girls, which would result in the negative correlations mentioned above.

It is now better to examine the changes of these two breadth variables in the context of allometry. Stature is used as the overall body size variable in the following discussion. For younger boys, shoulder breadth shows isometry against stature ($k=1.04$, ranging from 0.92 to 1.17), and hip breadth shows slightly positive allometry ($k=1.17$, ranging from 1.00 to 1.37). But for the boys examined after the onset of adolescence, the relative growth rate of the shoulders increased dramatically ($k=1.66$, greater than that of hip breadth which is 1.52). However, in girls, the pattern is different. In the younger group, the situation for shoulder breadth is similar to that of boys, but the allometric coefficient for hip breadth is much higher ($k=1.78$, ranging from 1.46 to 2.20). In older girls, in contrast to that of boys, the allometric coefficient for shoulder breadth shows a modest increase ($k=1.37$, ranging from 1.09 to 1.75), but is still close to isometry. However, for hip breadth, the coefficient has a value $k=2.18$. These results clearly indicate that after the onset of adolescence, with children of both sexes increasing their growth velocity, girls have higher growth acceleration for the hip, whereas boys increase for the shoulder. The chest has similar growth pattern to that of the shoulder. Its allometric coefficients for younger and older boys are 1.34 and 3.81 respectively, with a sharp increase between the two groups; for girls, they are 1.81 and 2.00, indicating little change. It is therefore clear that boys have a more rapid growth for the chest (See table 3.7 to 3.10).

For both sexes, most girth variables were found to show positive allometry in relation to stature. In girls, the results strongly suggest that their growth is towards a heavier type of body build. In limb girth variables, the only exception was for the wrist in boys, where isometry was found. Girls in general had a higher rate of allometric growth for girth variables than boys.

It is interesting to note that the proximal parts of the upper and lower limb are consistently found to have a greater allometric growth rate than the distal region. This observation was particularly significant for the girls. Taken together with the allometric analysis for hip breadth, it was found that girls principally achieve the body shape changes by enlarging the proximal part of the limbs and the pelvic region during growth (Table 3.5, 3.6).

Comparing the results of this study with that of Dangerfield (personal communication), it is found that for the three most used measurements, stature, body weight, and sitting height, the curves are very similar. As stated in 3.4 and illustrated in Figure 3a - 3c, it is suggested that the current sample may have its adolescent spurt one year earlier than the sample of Dangerfield, indicating an earlier maturity tendency of girls in Liverpool. An earlier maturity tendency, as secular trend, for children's growth has been widely reported in the world. Ljing *et al* (1974) reported that in the periods of 1883, 1938-1939, and 1965-1971, Swedish girls had their peak height velocity (PHV) age 12.8, 12.2, and 11.6 years old respectively; boys displayed a similar trend. Lin *et al* (1989) collected and analysed the last half century's children growth data for the main cities in China, and found that the PHV age reduced by 1-2 years in ten out of 12 cities from the fiftieth to eightieth decades. Tanner (1962) summarised the same phenomenon in the different countries. It is generally considered that this earlier maturity trend is companied by another common phenomenon, ie. for the same aged children, the later era ones have larger body size than the earlier ones. The later phenomenon is not shown in the comparison of current sample with that of Dangerfield. It suggests that, although the current sample has a one year growth spurt advantage, by the end of the second year the old sample has caught up, so that from this point onwards the two growth rates become similar again. A few other variables display a similar feature (Figure 3c, 3g, 3h, 3i, 3j). It has been reported that the earlier maturity tendency has ceased in developed countries in recent years. For example, Brundland *et al* (1973) found that the menarchal age in Oslo had not changed from 1952 to 1970. This might be an isolated phenomenon. Tanner (1962) believed at that time "there is little evidence at present that the trend has stopped" (Tanner, 1962, p. 154). Nearly thirty years later, it seems this secular trend is still occurring. However, in contrast, another widely accepted concept that the average body size of a population has ceased to increase in developed country is confirmed by the data included in this study.

Another possibility to explain the difference in the growth velocity at 12 years for the two Liverpool samples is social class. The current data have been collected in the schools which take children from relatively wealthy families, whereas Dangerfield's sample were from schools draw their children from predominantly 'lower' and 'middle' class families. However, Liverpool is not a prosperous city compared to the other parts of England.

The allometric coefficient of the cubic root of body weight on stature is 1.07 (range from 1.00 to 1.14) for boys and 1.31 (range from 1.21 to 1.43) for girls, indicating positive allometry of body weight against stature, ie. the cubic root of weight increases in relation to stature over the age range 8 to 16 years. It is interesting to compare these results with those of Marshall *et al* (1980) for boys aged from 7 to 16 years, and of Vadja *et al* (1980, for boys and girls aged from 6 to 13 years). Their results are listed in Table 4.1.

TABLE 4.1 Comparison of allometric coefficients with those of previous studies

Sex	Exponent	Source	Population
Boys	0.91	Marshall (1980)	Saskatchewan
Boys	0.89	Vajda (1980)	Belgian
Girls	0.85	Vajda (1980)	Belgian
Boys	1.07	Present	Liverpool
Girls	1.31	Present	Liverpool

The allometric coefficients in the papers of Marshall and Vajda were expressed in terms of body weight, not the cubic root of weight, against stature. For convenience in comparison, in Table 4.1, their results were divided by three. But, what is the explanation to the difference between their results and that of this study? It may be attributed to the random error in the sample, differences in the populations, or different sampling techniques (It should be noted both samples of Marshall and Vajda were longitudinal in nature). However, the author of this thesis believes that an important reason for the difference was due to the method used to estimate the value of allometric coefficient. Vajda *et al* did not disclose the method employed to calculate their coefficients. However, Marshall *et al* stated that they defined the slope 'b' by the least squares method. From the discussion above, it is known that the reduced major axis slope v is equal to v/r. Generally, r (correlation coefficient) of stature with body weight is about 0.9. In Marshall's study, the slope estimated by the reduced major axis method would be 0.91/0.9=1.01. This is closer to the result in the present study. The exponent estimated by the reduced major axis method for the boys' data of this study is 1.06 (not listed), which is practically the same as the value of the major axis slope (z=1.07) listed in the table.

Allometric analysis shows that boys and girls have different patterns in the change of their body shape. The results listed in Table 3.11 indicate that for boys, the younger age group has relatively more variables which display a higher allometric rate than the older boys. This suggests that boys slow down their body shape changes after the onset of adolescent growth. In contrast, younger girls have fewer variables with a higher rate of allometry than their older counterparts (the only three variables for which younger girls have higher allometric coefficients than older girls, ie. the lengths of tibia, foot, and total lower limb, have a difference which is not as large as that in boys). This suggests that girls, unlike boys, increase the rate of body shape change when they commence their major phase of body size increase.

The last two columns of Table 3.11 show that both before and after the onset of the pubertal growth spurt, girls show higher rate of allometric growth than boys, for most of the morphological variables. It could be concluded that girls have more shape changes during the growth period than boys. At and after adolescence, this difference is even more obvious, with girls accelerating, and boys decelerating, their body shape changes.

4.3.2 Biomechanical Characteristics

For the variables relating to the inertial properties, the centre of gravity and radius of gyration are expressed as the ratio of limb length, the limb segment volume is expressed as its absolute value and as a ratio to the whole body volume. It has been assumed that whole body has a specific gravity of one, based on the observation of Dempster (1955a). As a result, body weight in kilogrammes could be used as the volume in litres. As discussed earlier, these ratios describe 'shape', and the first two, the centre of gravity and the radius of gyration, are parameters which describe the mass distribution within a body segment.

Centre of gravity and radius of gyration have values which remain similar for different ages and sexes, and so display little change between groups. Jensen (1986) found that for these two variables, both adults and children had practically identical values. Bernstein (1931) also failed to find any difference in the value for centre of gravity between subjects at different ages. However, there are discrepancies among the results from different authors (see Tables 4.2 and 4.3). The present author believes that this may be due to the different ways adopted for defining limb segments.

The results of this study reveal that whereas the sex and age differences for the centre of gravity do exist, for volume ratio, the difference is more obvious. Centre of gravity and volume ratio also correlate with the size variable, even though the correlations are weak (Tables 3.5 and 3.6).

TABLE 4.2 Comparison of centre of gravity from different sources

Source	Hand	FA*	UA**	Calf	Thigh	FH***
Harless (1860)	36	44	48.5	44	43	45.8
Braune (1889)	-	42.1	49.0	42	44	-
Dempster (1955)	51	43.0	43.0	43.3	43.3	-
Clauser (1969)	-	39.0	51.3	37.1	37.2	-
Drillis (1966)	39.2	42.3	42.3	39.3	41.0	38.2
Chandler (1975)	51.2	41.2	52.0	38.8	42.2	-
Ackland (1988)	-	-	-	41.8	43.6	-
Zatziorsky (1983)	37.0	42.7	45.0	40.5	-	-
Bernstein (1931)	-	41.5	47.5	41.8	38.8	46.6
This study[1]	33.8	41.9	44.8	41.7	44.5	37.8

*FA: Forearm; **UA: Upper arm; ***FH: Forearm with Hand
1) Pooled sex sample

TABLE 4.3 Comparison of radius of gyration from different sources

Source	Hand	FA*	UA**	Calf	Thigh	FH***
Zatsiorsky (1983)[1]	28.5	29.5	32.8	28.1	-	-
	23.3	28.4	31.0	27.5	-	-
Drillis (1966)	-	-	26.0	27.0	23.0	25.0
Contini (1972)	26.7	29.2	27.2	28.1	28.1	-
Jensen (1978)	23.3	28.4	31.1	27.5	-	-
This study[2]	23.9	28.61	30.31	27.13	26.7	26.3

*FA: Forearm; **UA: Upper arm; ***FH: Forearm with Hand
1) The first row is in anteroposterior
the second is in transverse
2) Pooled sex sample

TABLE 4.4 Comparison of segment relative weight

Source	Hand	FA*	UA**	Calf	Thigh	FH***
Harless (1860)	0.9	1.7	3.2	4.6	11.9	2.6
Braune (1889)	0.8	2.1	3.3	4.8	10.7	2.9
Fisher (1906)	-	-	2.8	4.5	11.0	2.6
Berstein (1931)	0.70	1.82	2.66	4.66	12.2	-
Dempster (1955)	0.6	1.6	2.7	4.5	14.8	-
Drillis (1966)	0.57	1.70	3.50	4.08	-	-
Clauser (1969)	0.65	1.61	2.63	4.35	10.3	2.27
Zatsiorsky (1983)	0.61	1.63	2.71	4.33	-	-
Jensen (1978)[1]	0.9	1.7	3.2	5.3	11.0	-
This study[2]	0.69	1.62	2.84	4.90	-	-

*FA: Forearm; **UA: Upper arm; ***FH: Forearm with Hand

1) Subjects aged 12 years old

2) Pooled sex sample; Drillis' data for specific gravity were used to transfer volume into mass

Generally speaking, the centre of gravity of the hand (stretched) is located at a position two thirds of the hand length from the third finger tip, with a little variation (Table 3.2.40). For boys, there is no change among age groups. However, it appears that girls have a higher value in older age groups (F=3.0, $p<0.01$). The results suggest that for girls there may be more growth in the palm than in the fingers, resulting in a proximal displacement of the centre of gravity.

Both sexes show age changes in the position of centre of gravity in the upper arm, with its position becoming more and more proximal with increasing age; the change is more marked in boys (F=3.8, $p<0.01$). This is considered to be due to the development in the muscles around the shoulder end of the humerus, ie. deltoid. The development of these muscle enlarges the cross-sectional area of the proximal part of the upper limb, so that the centre of gravity moves towards the proximal end. Among previous studies, the only comparable one, undertaken on young adults by Drillis and Contini (1966), showed that the value for this variable was 57.7, which is slightly higher than the value for the oldest age group in this study.

Differences between sexes and among age groups in girls were found for the centre of gravity of the forearm with hand. Table 3.4 indicated that at age 9, 11, and 13 years old, girls have a higher value for this variable at significance level $p < 0.20$; at age 10 to 15, this difference is more significant ($p < 0.05$). This indicated that girls have a larger forearm in relation to their hand. The 'F' value suggests ($F = 4.2$, $p < 0.01$) that older girls tend to have an even higher value for this variable, a trend not seen in boys.

The other two multi-segment upper limb units, the centre of gravity of upper arm with forearm, and that of upper limb, also show age related changes and sex differences. For these two variables, the situation is similar to that of the forearm with hand, except boys also display significant age-related changes for the two variables. Taking all the above discussion into account, the author believes that the sex difference is mainly due to the change in hand. It is interesting here to examine the radius of gyration of the upper limb. RG is a parameter which remains steady during growth with the result that age differences are rarely found (Tables 3.2.56-3.2.63). However, the upper limb is an exception. It is observed that the RG of upper limb becomes less with increasing age. This phenomenon is not easy to explain. However, boys tend to have greater value for RG of the whole upper limb. As an analogue, a dumb bell has a larger RG value than a bar.

The centre of gravity of the calf also shows age change in girls ($F=2.6$, $p<0.01$). It appears that girls initially increase the CG value for the calf, but that this then decreases again with age. Boys have a similar pattern, but it is not statistically significant ($F=0.8$).

The correlation of the centre of gravity in ratio to limb length with size variable is low. Figure 4.2 shows this relationship.

Generally speaking, boys display higher values for the upper limb volume to body volume ratio; this is believed to be due to the differences in hand and forearm. For the upper arm, no sexual dimorphism is seen. In the growth period, changes occur in the hand and forearm, especially in the former. For the upper arm, no change with age can be detected for boys and girls. It was found that in both sexes, the hand and forearm reduce their relative volume when children grow up; this trend is much obvious in girls than in boys. It implies that girl have a gain in the volume ratio for some parts of their bodies (which could not be found by the study). However, this finding did confirm that girls have much more changes in body shape during growth, which has already been shown by allometric analyses of morphological variables.

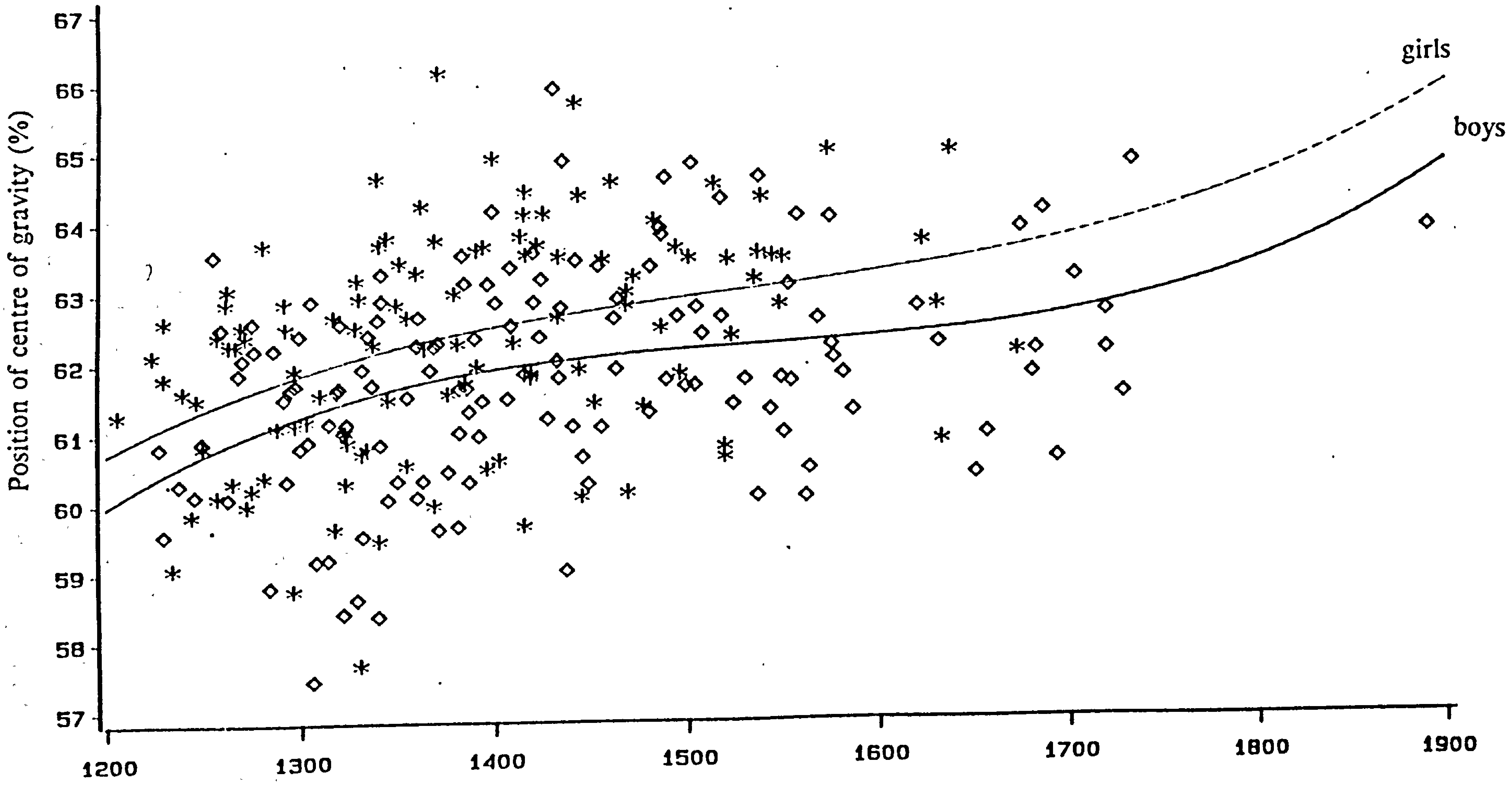


Fig. 4.2 Relationship between centre of gravity of upper limb and stature

Inter-segment changes , like those within segments, demonstrate the trend that the distal parts of limbs get relatively smaller with increasing age. Tanner (1962) claimed that for limb length, distal segment is always closer to mature status than proximal one. The results of this study reveal that Tanner's (1962) conclusion is true not only for length, but also for volume.

Unlike other segments, sexual dimorphism of hand volume exists for both absolute and relative values. From the age of 8 years old, boys display higher values for hand volume, and they maintain this pattern throughout the whole growth period. Only at age 13 do both sexes have the same value, at a time when girls have already finished their growth spurt whereas boys have just begun. During the years after this, boys show a sharp increase in hand volume, while girls see little growth. The author speculates that the variables showing pre-adolescent sexual dimorphism, such as bicondylar diameters and hand volume, have been subject to rigorous sexual selection in human evolution.

Among previous studies in the field of human body inertial characteristics (Table 4.2 to 4.4), few have been undertaken using children as research subjects. The only results comparable with this study were those of Jensen (1981), Ackland *et al* (1988), and Yokoi *et al* (1985). However, Ackland *et al* did not report the data for the upper limb, and Jensen and Yokoi displayed their results mainly by charts, with the result that their data are sometimes not available for comparison.

Jensen (1986) showed in his study that both the upper and lower limb gained in mass ratio (in relation to body weight) during the ages of 4 to 15 years. Foot volume was not investigated in the current study, while the volume of thigh was estimated by an ellipse-modelling technique. Considering that this method is not very accurate, the results were believed to have limited value; the author therefore did not calculate the ratio of thigh to body volume. However, although the calf mass (or volume) ratio for girls did not display the same trend which Jensen had shown, similar differences were found for the segments of upper limb in both sexes. As mentioned in the literature review, Jensen used regression slopes to make his point, but failed to provide statistical support for the regression. His charts seemed to suggest that the hand and forearm had the same ratio throughout the whole age range studied, (whereas Jensen claimed, without apparent evidence, that these ratios were increasing with age), while upper arm was increasing its ratio to whole body mass. The current study shows the reverse pattern. The reason for this difference is not clear. One possible explanation is the sampling technique. Jensen's sample was a selected small sample, whereas a more random sample was used in the present investigation. Population difference may also be a potential reason; Yokoi *et al* (1985) showed that, in Japanese children, both the thigh and calf increase their mass volume, but Zook (1932) suggested that in the USA, boys maintained the constant values for these two ratios, or even a diminished value for the ratios. Zook also concluded that poorly nurtured boys had relatively larger leg volumes.

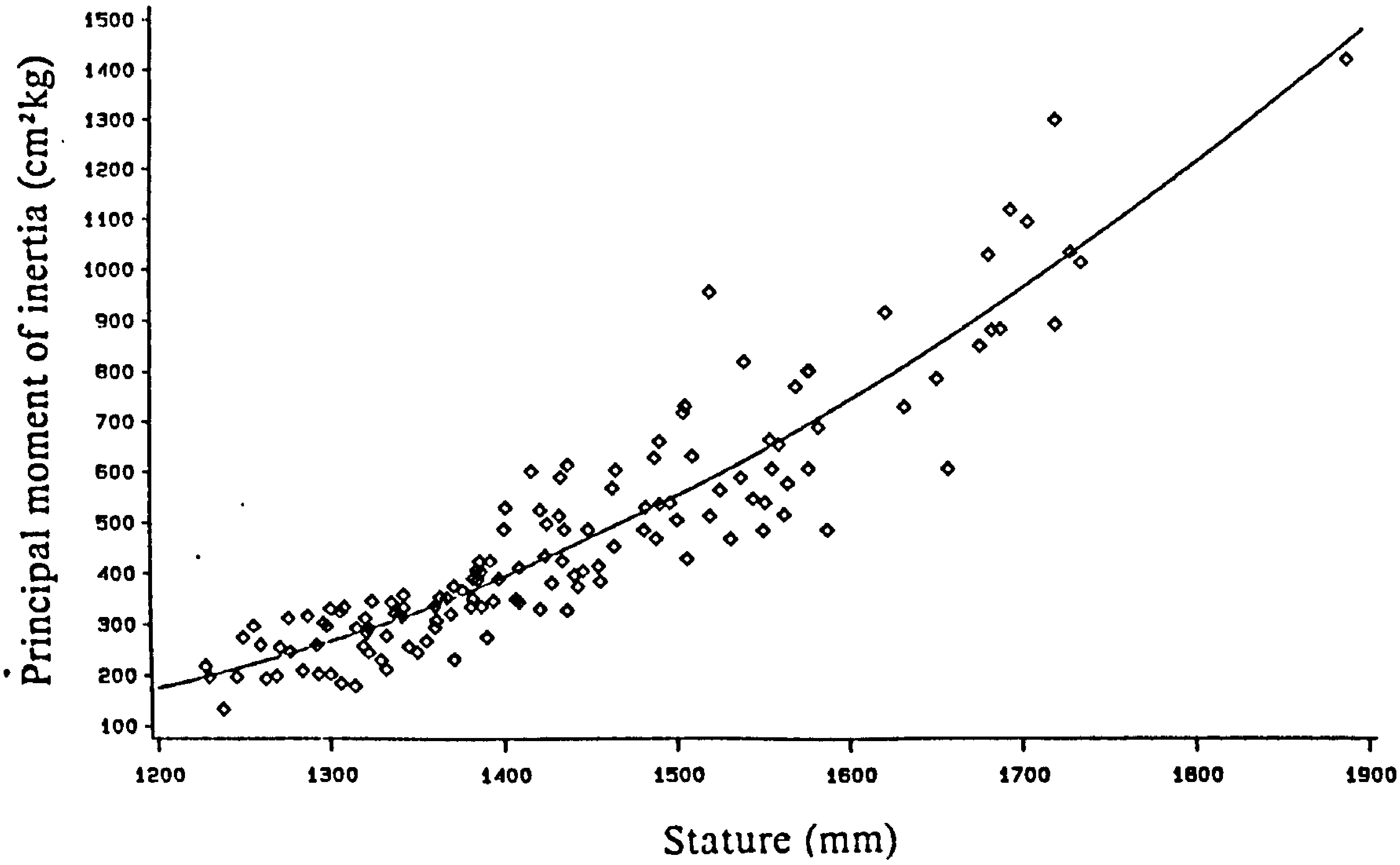


Fig. 4.3a Relationship between principal moment of inertia of upper limb and stature (Boys)

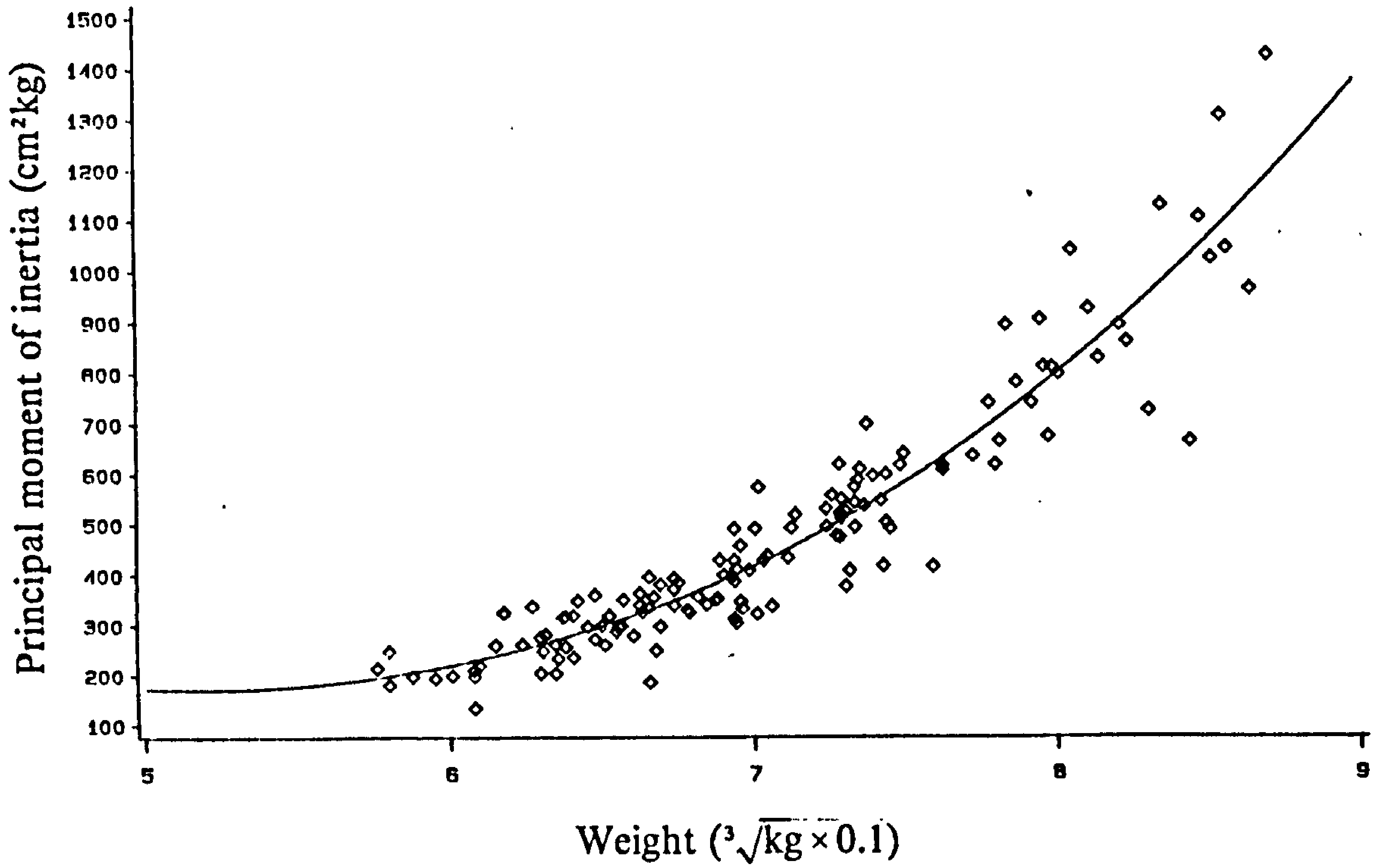


Fig. 4.3b Relationship between principal moment of inertia of upper limb and weight (Boys)

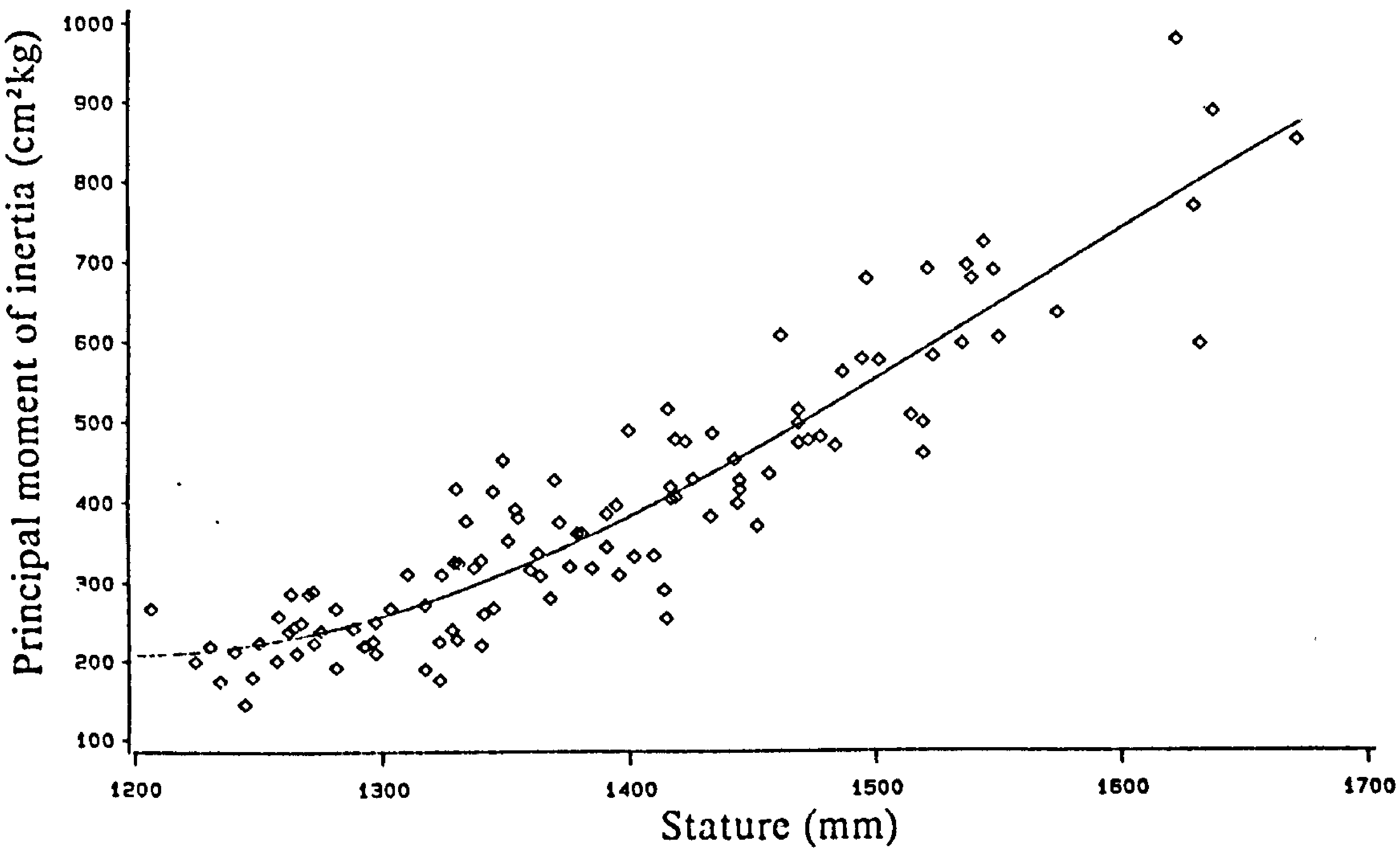


Fig. 4.4a Relationship between principal moment of inertia of upper limb and stature (Girls)

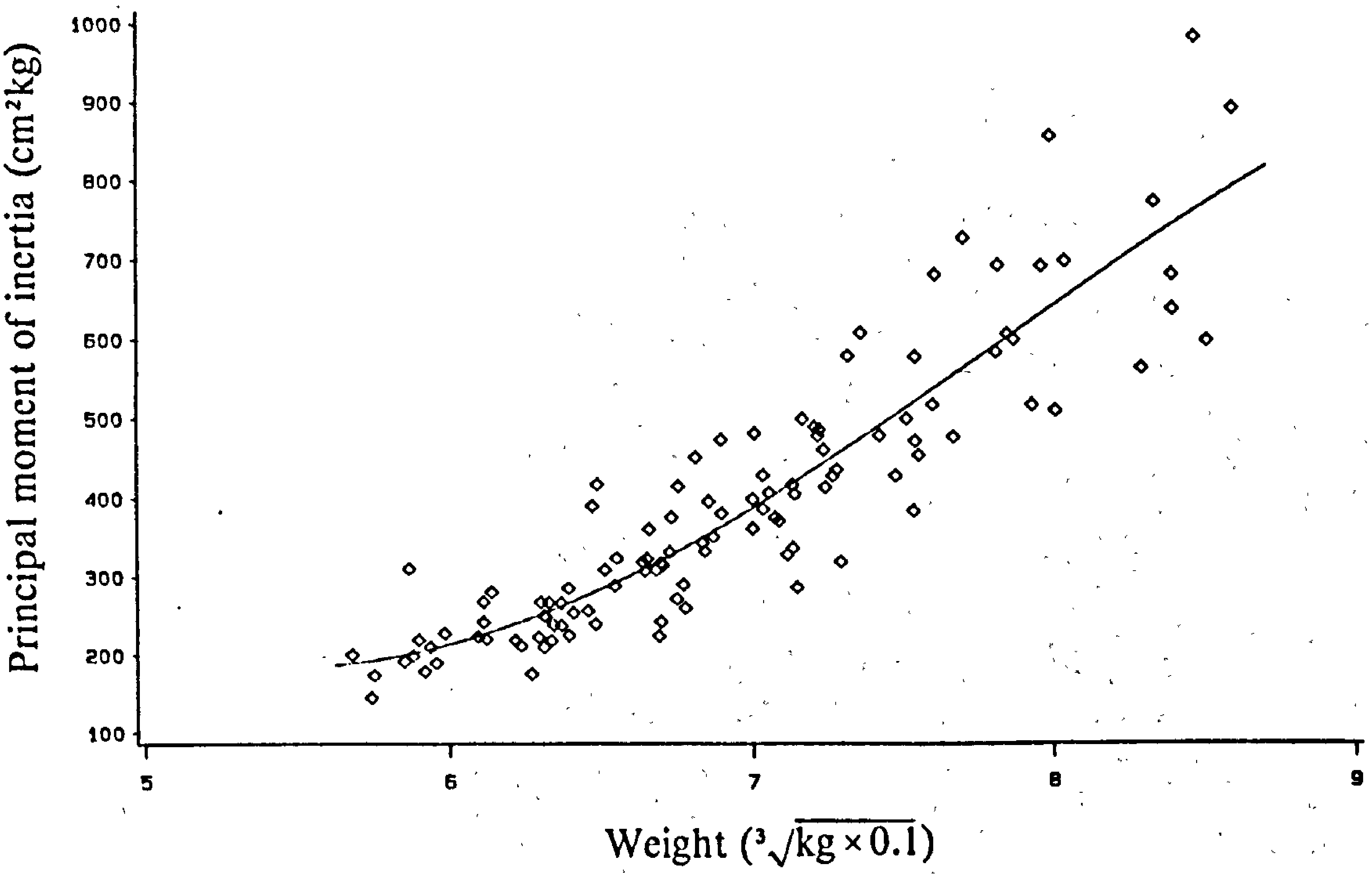


Fig. 4.4b Relationship between principal moment of inertia of upper limb and weight (Girls)

Table 4.2 lists the results of the previous studies of the centre of gravity. Due to differences in defining the body segments, and differences in the measurement technique, the results were so different that it is hard, if not impossible, to compare them. However, for the centre of gravity, the results from living subjects (Drillis, Ackland, Zatziorsky, Bernstein, and the current study) are in general similar. It is believed that a cadaveric study, because a direct method was used, should achieve better precision. This survey suggests that further research into the distribution of the centre of gravity within human body segments is still needed. In contrast, for the radius of gyration, the results are consistent. The only exception is for data on the hand. Zatziorsky's data suggested that the results for the radius of gyration of the hand in this study, and from that of Jensen, are the radius of gyration about a transverse axis; for that about anteroposterior axis, the value is much larger. However for other segments, the results for the two axes are similar. Chandler *et al* (1969) also found similar results. In discussing the value of principal moment of inertia, they stated "I_{xx} and I_{yy} are approximately of the same magnitude for the major limb segment" (p. 99, note RG=PMI/M, so Chandler's statement meant $RG_{xx} \approx RG_{yy}$). The results demonstrated the validity of assuming the cross-sectional shape of a limb segment to be a circle, which was the methods used in the calculation of the principal moment of inertia in this thesis.

The principal moment of inertia and volumes are the parameters which are closely correlated with the body size. By theory, based on a geometric similarity model, they are the linear dimension raised to the fifth and cubic powers respectively. Figure 4.3 and 4.4 illustrates the relationships of principal moment of inertia with stature and body weight.

For the principal moment of inertia, little sexual difference can be detected until age of 15 years, when boys display a higher value for the majority of the variables. By definition the moment of inertia (including the principal moment of inertia) of an object depends largely on the length of its radius. It is reasonable to assume that any difference in PMI at 15 years old between the sexes is due to the difference in limb length.

In the comparison among the available data of the principal moment of inertia, it is found that the results from different authors differ fundamentally. The randomly distributed difference suggested that a dominant error source would be the definition on the segments. For in case either sample or measurement technique difference, a system error for all the segments should have been demonstrated, and the results should be correlated among the different sources.

There is a paradox in using major axis slope to estimate allometric coefficients for moments of inertia, volume and perhaps other high-dimension variables. Theoretically, the MI and volume (or mass) are the fifth and third power of linear dimension respectively, so that they were standardised in advance before allometric analysis. For example, the dimension of a PMI datum was L^5, after being standardised it would be L, or logL in logged form. However, if it had not been transformed by fifth root operation, it would have had a logged form $5 \times \log L$. As discussed earlier, the major axis slope does not change linearly with a linear change in data, ie. the slope of 5 × logL against logL is not five, but a higher value. This fact suggests that for variables with unknown properties, the major axis slope might give a misleading result in allometric analysis. In this case, a geometric mean slope is safer. Another possible method to overcome this problem of major axis slope is iteration, to determine a value with which the standardised data has an isometric relationship with the independent variable.

The stepwise regression procedure generally gives a practical formula to estimate the value of dependent variables. It is not necessary for the independent variables which have entered and stayed in the regression equation to have a logical relationship with the variable predicted. For example, in the equation for the volume of the hand, it is possible for neither hand length nor hand breadth to be a regressor, but forearm length is used in the equation instead. This is because the information about the length and breadth of the hand are expressed by forearm length. However, in this study, it is noticeable that the girth of upper arm is important in predicting values of the centre of gravity and radius of gyration of upper limb segments in both boys and girls, with only two exceptions in CG of girls (Tables 3.11 and 3.12). There should be a logical explanation for this. The author believes that, compared with forearm girth, the girth of upper arm more faithfully represents the morphological, or 'shape', characteristics of the upper extremity. These two tables also shows that for the centre of gravity and radius of gyration of multi-segments, girls have better prediction effects (higher values for R). This could be explained as that girls' limbs have more regular inter-joint shape changes.

In studies such as human movements or ergonomics, a human body model is essential, and there has been a considerable research activity in this field. However, serious shortcomings can be identified in the previous studies. In these investigations, attention was paid to the geometric dimensions and the kinematic properties, such as the circular movement centre of a limb joint, then to the centre of gravity and volume of mass of body parts, which represent the static property of a human body (Dempster, 1955b; Contini, 1972; Roebuck *et al,* 1975; Li, 1984). The most sophisticate inertial property model of human body was that of Hanavan (1964), who took account not only of all the above variables, but also a more dynamic factor, the moment of inertia. Hanavan used a series of truncated cones to represent human body segments in his model. However, Hanavan's work still cannot be considered wholly satisfactory, since he simply used morphological anthropometric variables to construct his model. For example, he took proximal and distal upper arm girths as the circumferences of the two ends of truncated cone which composed his model of the upper limb. As the result, his model can hardly guarantee any true values for mechanical characteristics of the human body.

A improved method can solve Hanavan's problem. A truncated cone (with unit length) can still be used as geometrical model in this method (Chapter 2.4 and 3.4). Given the required values for the centre of gravity and radius of gyration, formulas (1) and (2) in 2.4 can be used to calculate the relevant values for parameters of the model: radius r_1 and ratio $s = r_2/r_1$. This model guarantees that the centre of gravity and radius of gyration have the required values. For example, if a limb segment has $RG = 0.273$, $CG = 0.625$, it can be represented by a truncated cone with radius 0.0644 (in relation to the length) for one end, and 0.0644 × 2.303 for the other end (Appendix II).

The above discussion refers to a solid of revolution formed by revolution of a straight line, $y=(r_2-r_1)z+r_1$, about axis OZ. If a parabola $y=(r_2-r_1)\surd z+r_1$ is used to form this solid of revolution, the method can be further improved. However, models constructed with this procedure have a shortcoming: they have only two independent variables, ie. r_1 and r_2, so that they cannot simultaneously satisfy three parameters, say, centre of gravity, radius of gyration, and mass, of a limb (with these three parameters, the principal moment of inertia can be calculated as $PMI=RG^2M$ and the moment of inertia about a end of the limb can then be obtained as $MI=PMI+ CG^2M$. The way to overcome this problem is to add an additional independent variable into the model. For example, a truncated cone with a hole along the z axis. In this case, the length (l) of a limb must be taken into account:

$$CG=\frac{\pi\int_0^l [(r_1+zr_2-zr_1)^2-R^2]zdz}{\pi\int_0^l (r_1+zr_2-zr_1)^2dz-\pi R^2 l}$$

$$M=\pi\int_0^l [(r_1+zr_2-zr_1)^2zdz-\pi R^2$$

$$CG^2 + RG^2 = \frac{PMI}{M} = \frac{\pi \int_0^l [0.25(r_1^4 - R^4) + (r_1^2 - R^2)z^2]zdz}{M}$$

where R ($R < r_1 < r_2$) is the radius of the hole, and M is mass. The model defined from these three-variable simultaneous equations will satisfy biomechanical characteristics of the centre of gravity, mass, radius of gyration, as well as that of length. The solid formed by revolution of some other curves y=f(z) will be better than this linear model, but on the other hand, a more complicated mathematical operation is needed.

4.4 FURTHER STUDY REQUIRED

The study of human body mechanical characteristics has been undertaken for over one hundred years, and many scientists have made substantial contributions to this field. However, there are some problems which need further improvement.

The first problem is that the study of human body inertial characteristics is multi-disciplinary; it requires a knowledge of anatomy, mathematics, mechanics, statistics, anthropology, and different measurement techniques, such as anthropometry, image processing, photographic, and so on. This knowledge is essential, not only for prosecuting a research project, but also for communicating with other workers. Due to lack of mechanical expertise, Cleveland (1955) used a uncorrected theory for his project, resulting in a serious error in his results. Some of the irrelevant conclusions of Clauser *et al* (1969) on Bernstein *et al* (1932) and Drillis *et al* (1966), are also attributable to lack of detailed familiarity with all the topics outlined above.

The second problem is that of the definition of body parts. In the previous studies, it is hard to find an identical definition of a body segment between any two authors. This indicates that the study of human body inertial properties is not a mature field. Previous work have shown that while a slight displacement of segment boundary has little effect on the percentage values of the centre of gravity and radius of gyration, the moment of inertia is more sensitive to boundary displacements. The boundary should be defined with proper anatomical landmarks, and should take account of mechanical features of the segment in question. In fact, many works such as those of Dempster (1955a), and Chandler *et al* (1975) had very good definitions. However, they need to be standardised for further study.

Last, but not the least, is the sampling strategy and the measurement technique adopted. The present author believes cadaver specimens produce bias, either as individuals or as a sample. Although there are difficulties in measuring living subjects, they can be overcome by modern technology. Magnetic imaging or stereophotographic techniques may well play an important role in the future data collection.

The results of the current study, and those of previous work, demonstrate that mass (or volume) and moment of inertia of most body segments are strongly correlated with anthropometric variables, so that it is easy to create regression equations to calculate them. While the centre of gravity and radius of gyration (in percentage to segment length) have a smaller variance, their prediction is not as important. The regressors for prediction equations should be local variables, ig. use only variables for the forearm for predicting inertial properties of forearm, and so on. The effects resulting from whole body shape change can therefore be reduced to minimum. In this way, the equations created would be more general, and could thus be applied to different populations.

5 CONCLUSIONS

There have been a number of investigations of children's growth and human body inertial characteristics. However, relatively few authors have used the latter as variables to study the former. This study has examined this relationship.

There have been a number of detailed studies of biomechanical properties of the human body. Data for the main parts of the human body are already available from a number of sources. However, agreement among these data are poor. Furthermore, few data are available for non-Caucasian populations.

The segment-zone-water-displacement method has been adopted and the volume distribution data of the limb segments obtained. Based on the work of Bernstein and others (1931), it is believed that these volume data can be used in place of mass data to estimate the position of centre of gravity of the limbs. The values of the principal moment of inertia have also been calculated from these volume distribution data, taking account of the value of specific gravity derived by Dempster (1955a).

When the moment of inertia was calculated, the limb in question was assumed to be a solid of revolution formed by a line around axis Z, so that all the cross sections along axis Z are circles and $I_{xx} = I_{yy}$. Previous works (Chandler *et al,* 1975; Jensen, 1978; Ackland *et al,* 1988) have shown that this truncated cone model did not compromise the validity of the data results. The radius of gyration and volume of the limb segments were also calculated from the volume distribution data. Mathematical analysis has shown that inertial characteristics are not sensitive to random error in mass distribution data obtained with segment-zone-water-displacement method, especially in the calculation of centre of gravity.

Conventional anthropometric measurements have also been undertaken in this study. Detailed analysis shows that the bicondylar diameters of both the humerus and femur demonstrate pre-adolescent sexual dimorphism, in which boys have an advanced development. This observation is unique and not displayed by other variables. Another pre-adolescent feature of sexual dimorphism was found in the index of hip breadth/shoulder breadth, in which girls were found to have higher mean values in each age group. It has also been shown that the co-relationships of the variables in boys and girls are very different.

Sexual dimorphism and body shape changes with age were studied by allometric analysis. It was found that girls undergo more body shape changes during growth than boys, ie. girls have a higher level of allometry for most variables. An important difference in body shape change between boys and girls occurs after onset of the adolescent growth spurt, in which girls accelerate, while boys decelerate, their body shape changes for the majority of the variables.

For the limb segments, the proximal parts have a higher allometric growth rate than the distal parts for both sexes. This shape change is also reflected in the centre of gravity. When children grow, the position of centre of gravity of their limbs has been found to move towards the proximal part of the limb.

The practical formula describing the relationship of changes in body shape with body size, $Y=AX^k$, has been shown to be a very useful method of analysis. It reflects the relative growth velocity of two variables. However, like most statistical methods, it is not a 'mechanical' or automatic procedure. Misleading results might occur if the procedure is incorrectly followed. There are several 'pit falls' in the use of the formula. Firstly, it is essential to choose the best way of estimating the parameter k used in the formula. Major axis regression is proposed to be the best method of achieving this, with reduced major axis regression as a substitute in certain circumstances. Secondly, in a growth study, the allometric coefficient, k, is best estimated over a short age interval. Finally, if the major axis regression method is used, special attention should be paid to the relationship between any X and Y data which have different dimensions.

The centre of gravity is the mean of mass distribution of a body, whilst the radius of gyration is the standard deviation, assuming the diameter of the body is small in relation to its length. These two characteristics can be used as parameters to describe the shape of the body in question.

The relative position of the centre of gravity of children was found to become lower in the body during their growth. It appears that this shape change ceases about ages 11-12 years in both sexes. The distance between the centre of gravity and the distal end of a limb, expressed as a percentage of the segment length, has a very small variance; the variance of radius of gyration is even smaller. These two sets of variables demonstrated differences between the sexes; difference among ages was only seen in the centre of gravity. For multi-segment units (eg. forearm with hand), these difference are more obvious. Generally speaking, the position of the centre of gravity of a limb segment moves towards the proximal end of that segment during growth. For both of these two sets of variables it was found that they could be predicted from anthropometric variables using the regression method. However, only the prediction of multi-segment limb units was considered to be satisfactory.

Volume and principal moment of inertia are 'size-correlated' variables, with their values increasing with age. There are little differences relating to age or sex to be found in volume variables. However, significant changes with age and sex have been revealed in the ratio of segment volume to body volume. For the variables of the moment of inertia and volume, a high correlation with anthropometric variables was demonstrated so that good regression equations could be created. They could be calculated from the equations with high accuracy.

Mathematical models in the form of a truncated cone for human limb segments can be created. These models satisfy the required values for length, mass, centre of gravity, radius of gyration, and principal moment of inertia. A simpler model, however, can satisfy the value of the two shape parameters, centre of gravity and radius of gyration. It is considered that these models may prove important in studies of sports and ergonomics.

REFERENCES

Ackland, T. R., Blanksby, B. A., and Bloomfield, J., 1988. Inertial characteristics of adolescent male segments. *Journal of Biomechanics* **21**: 319-327.

Albercht, G. H., 1978. Some comments on the use of ratios. *Systematic Zoology* **27**: 67-71.

Atchley, W. R., Gaskins, C. T., and Anderson, D., 1976. Statistical properties of ratios I, Empirical results. *Systematic Zoology* **25**: 137-148.

Atchley, W. R., 1976. Ratios and the Statistical analysis of biological data. *Systematic Zoology* **27**: 71-78.

Atchley, W. R., 1976. Ratios, regression intercepts, and the scaling of data. *Systematic Zoology* **27**: 78-83.

Attallah, N. L., 1980. *Growth of the limbs and their segments during childhood and adolescence: A photogrammetric study.* Doctoral thesis. University of London.

Barter, J. T., 1957. *Estimation of the mass of body segments.* Wright-Patterson Air Force Base (WADC TR 57-260), Ohio.

Becker, E. B., 1972. Measurement of mass distribution parameters of anatomical segments, pp 160-185. In: *Proceedings of sixteenth stapp car crash conference.* Society of automotive engineers report 720964. New York.

Bernstein, N., A., 1931. Salzgeber, O. A., Pavlenko, P. P., and Curvich, N., A., 1931. *Determination of location of the centers of gravity and mass of the links of living human body* (in Russian). All-Union Institute of Experimental Medicine, Moscow.

Bernstein, N., 1967. *The co-ordination and regulation of movements.* Pergamon Press.

Borelli, G. A., 1680-1681. *De Motu Animalium.* Lugduni Batavorum.

Braune, W., and Fischer, O., 1889. Uber den Schwerpunkt des menschlichen Korpers mit Rucksicht auf die Ausrustung des deutschen Infanteristen. Abh. d. math.-phys. cl. d. K. Sachs. Gesselsch. der

Wiss., 26, 561-672. In: *Human mechanics-four monographs abridged,* eds: Korgman, W. M. and Johnston, F. E. Wright-Patterson Air Force Base, Ohio, 1963 (AMRL-TDR-63-123).

Brooks, C. M., 1973. *Validation of the gamma mass scanner for determination of center of gravity and moment of inertia of biological tissue.* Master's thesis, The Pennsylvania State University.

Brooks, C. B., Jacobs, A. M., 1975. The gamma mass scanning technique for inertial anthropometric measurement. *Medicine and Science in Sports* 7: 290-294.

Brundland, G. H., Walloe, L., 1973. Menarcheal age in Norway; halt in the trend towards earlier maturation. *Nature* **241:** 478-479.

Cameron, N., Tanner, J. M., and Whitehouse, R. H., 1982. A longitudinal analysis of the growth of limb segments in adolescence. *Annals of Human Biology* 9: 211-220.

Carter, J. E. L., 1975. *The Heath-Carter somatotype method,* revised, San Diego State University, San Diego.

Carter, J. E. L., Ross, W, D., Duquet, W., and Aubry, S. P., 1983. Advances in somatotype methodology and analysis. *Yearbook of Physiscal Anthropology* 26: 193-213.

Casper, R. M., 1971. *On the use of gamma mass scanner for determination of human body segment parameters.* Master's thesis, Pennsylvania State University.

Casper, R. M., Jacobs, A. M., Kenney, E. S., and McMaster, I. B., 1971. On the use of gamma ray images for determination of human body segment parameters. Paper presented at quantitative imagery in biomedical sciences, Houston, Texas.

Chandler, R. F., Clauser, C. E., McConville, J. T., Reynolds, H. M., and Young, J. W., 1975. *Investigation of inertial properties of the human body.* Aerospace Medical Research Laboratory. AMRL-TR74-137.

Chatfield, C., and Collins, A., 1980. *Introduction to multivariate analysis.* Chapman and Hall.

Clauser, C. E., McConville, J. T., and Young, J. W., 1969. *Weight, volume and centre of mass of segments of the human body.* AMRL Technical Report 69-70, Wright-Patterson Air Force Base, Ohio.

Cleveland, H. G., 1955. *The determination of the center of gravity of segments of the human body.* Doctoral dissertation, University of California, Los Angles.

Contini, R., Drillis, R., and Bluestein, M., 1963. Determination of body segment parameters. *Human Factors* 5: 493-504.

Contini, R., 1972. Body segment parameters, part II. *Artificial Limbs* 16: 1-19.

Damon, A., and McFarland, R. A., 1955. The physique of bus and truck drivers: with a review of occupational anthropometry. *American Journal of Physical Anthropology* 13: 711-742.

Dangerfield, P. H., 1984. *A study of neonatal measurements.* Doctoral thesis, University of Dundee.

Dempster, W. T., 1955a. *Space requirements of the seated operator.* WADC Technical Report 55-159, Wright-Patterson Air Force Base, Ohio.

Dempster, W. T., 1955b. The anthropometry of body action. *Annals New York Academy of Science* 63: 559-585.

Dodson, P., 1978. On the use of ratios in growth studies. *Systematic Zoology* 27: 62-67.

Drillis, R., Contini, R., and Bluestein, M., 1964. Body segment parameters - A survey of measurement techniques. *Artificial Limbs* 8: 44-66.

Drillis, R., and R. Contini, 1966. *Body segment parameters.* Report No. 1163-03, Office of Vocational Rehabilitation, Department Health, Education and Welfare, New York.

Duggar, B. C., 1962. The centre of gravity of the human body. *Human Factors* 4: 131-148.

Duquet, W., and Hebbelinck, M., 1977. Application of the somatotype attitudinal distance to the study of group and individual somatotype status and relations. In: Eiben, O. (eds) *Growth and Development; Physique.* Budapest: Akademiai Kiado, pp. 377-384.

Elsholtz, J. S., 1672. *Anthropometria.* Editio post Patavinam altera. Stade: E. Dohlium.

Fisher, O., 1906. *Theoretische Grundlagen Fur eine Mechanik der Lebenden Korper mit Speziellen Anwendungen auf den Menschen sowie auf einige Bewegungsvorgange an Maschinan.* Leipzig: Teubner.

Fujikawa, K., 1963. The center of gravity in the parts of human body. *Okijimas Folia Anatomy,* 39: 117-125.

Gould, S. J., 1966. Allometry and size in ontogeny and phylogeny. *Biological Review* 41: 587-640.

Gray, M. A., 1963. *An analytic study of man's inertial properties.* MS Thesis, U. S. Air Force Institute of Technology. Wright-Patterson Air Force Base, Ohio.

Hanaven, E. P., 1964. *A mathematical model of the human body.* AMRL Technical Report 64-102, Wright-Patterson Air Force Base, Ohio.

Hansman, C., 1970. Anthropometry and related data. In: McCammon, R. W., *Human growth and development.* C.C. Thomas, Springfield. Ill., pp. 101-154.

Harless, E., 1860. *The static moments of the component masses of the human body.* Wright-Patterson Air Force Base, Ohio, 1962 (FTD-TT-61-295).

Hattori, K., 1975. Age change of allometry coefficients in Japanese. *Journal. Anthropological Society of Nippon* 83: 29-38.

Hatze, H., 1975. A new method for the simultaneous measurement of the moment of inertia, the damping coefficient and the location of the centre of mass of a body segment in situ. *European Journal of Applied Physiology and Occupational Physiology* 34: 217-226.

Hatze, H. 1980. A mathematical model for the computational determination of parameter values of anthropometric segments. *Journal of Biomechanics* 13: 833-843.

Hay, J. G., 1973. The centre of gravity of the human body. In *Kinesiology 1973.* Washington: AAHPER, 1973.

Harvey, P. H. and Mace, G. M., 1982. Comparisons between taxa and adaptive trends: problems of methodology. In: *Current problems in sociobiology,* pp 343-361. eds. King's College Sociobiology Group, Cambridge. Cambridge University Press.

Hebbelinck, M. and J. Borms, 1984. Sexual dimorphism in body build of 6 to 13 year-old boys and girls. In: *Human Growth and Development.* pp. 287-301. eds. J. Borms, et al. Plenum Press, New York and London.

Herron, R. E., Cuzzi, J. R., Goulet, D. V., Hugg, J. E., 1974. *Experimental determination of mechanical features of adults and children.* U.S. Department of Transportation. DOT-HS-231-2-397.

Herron, R. E., Cuzzi, J. R., Hugg, J. E., 1976. *Mass distribution of the human body using biosterometrics,* AMRL-TR-75-18.

Hersh, A. H., 1941. Allometric growth: The ontogenetic and phylogenetic significance of differential rates of growth. *Growth* 5: 113-145.

Hersh, A. H., 1955. Allometry and anthropometry. *Annals New York Academy of Science* 63: 484-490.

Hills, M., 1978. On ratio - a response to Atchley, Gaskins, and Anderson. *Systematic Zoology,* 27: 61-62.

Hills, H. and Wood, B. A., 1984. Regression lines, size, and allometry. In: *Food Acquisition and Processing in Primates.* eds: Chiver, D. J., Wood, B. A., and Bilsborough, A., pp 557-567. London: Plenum Press.

Hinriches, R. N., 1985. Regression equations to predict segmental moments of inertia from anthropometric measurements: A extension of the data of Chandler *et al* (1975). *Journal of Biomechanics* 18: 621-624.

Huxley, J. S., 1924. Constant differential growth ratios and their significance. *Nature* 114: 895.

Huxley, J. S., 1932. *Problems of relative growth.* Methune & Co. London.

Jensen, R. K., 1978. Estimation of the biomechanical properties of three body types using a photogrammetric method. *Journal of Biomechanics* 11: 349-358.

Jensen, R. K., 1981. Age and body type comparisons of the mass distributions of children. *Growth* 45: 239-251.

Jensen, R. K., 1986. Body segment mass, radius and radius of gyration proportion of children. *Journal Biomechanics* 19: 359-368.

Jensen, R. K., 1987. Growth of estimated segment masses between four and sixteen years. *Human Biology* 59: 173-189.

Katch, V., Weltman, A., and Gold, E., 1974. Validity of anthropometric measurements and the segment-zone method for estimating segmental and total body volume. *Medicine and Science in Sports,* 5: 271-276.

Laird, A. K., 1965. Dynamics of relative growth. *Growth,* 29: 249-263.

Laubach, L. L. and McConville, J. T., 1967. Notes on anthropometric technique: anthropometric measurements - right and left sides. *American Journal of Physical Anthropololy* 26: 367-370.

Li, Y., 1985. A discussion on auto cab workspace and design of driver's chair. *Acta Anthropologica Sinica,* 4: 333-344.

Li, Y., Dangerfield, P. H. and Wood. B. A., 1990. Allometry and sexual dimorphism in the growth of limb segments in British children (abstract). *Journal of Sports Sciences* 8: 180-181.

Li, Y., Dangerfield, P. H. and Wood. B. A., 1990. Predicting the mechanical characteristics of the human limb using conventional anthropometric variables (abstract). *Journal of Sports Sciences* 8: 181.

Lin, W., Xiao, J., and Ye G., 1989. Secular trend of growth in Chinese Han Nationality children. *Acta Anthropologica Sinica,* 8: 355-366.

Liu, Y. K., Laborde, J. M., and Van Buskirk, W. C., 1971. Inertial properties of a segmented cadaver trunk: their implications in acceleration injuries. *Aerospace Medicine* 42: 650-657.

Ljing, B. O., Agneta, B. B., and Lindgren, G., 1974. The secular trend in physical growth in Sweden. *Annals of Human Biology,* 1: 245-256.

MacDougall, J. D., Wenger, H. A., 1982. *Physiological Testing of the Elite Athlete.* Canadian Association of Sport Sciences, Sport Medicine of Canada Mutual Press.

Malina, R. M., 1974. Adolescent changes in size, build, composition and performance. *Human Biology* 46: 117-131.

Marshall, G. R., Bailey, D. A., Leahy, R. M., Ross, W. D., 1980. Allometric growth in boy of ages seven to sixteen years studied longitudinally. In: *Kinanthropometry II.* eds. Ostyn, M. and Beunen, G., University Park Press, Baltimore.

Marshall, W. A., 1978. Puberty. In: *Human Growth II,* eds: Falkner, F. and Tanner, J. M., Bailliere Tindall, London.

Martin R. and Saller, K., 1957. *Lehrbuch der Anthropologie,* Gustav Fisher Verlag, Stuttgart.

McConville, J. T., Clauser, C. E., 1976. Anthropometric assessment of the mass distribution characteristics of the living human body. In: *Proceedings of the Sixth International Ergonomics Association.* pp. 379-383. Maryland.

McMahon, T. A., 1984. *Muscles, Reflexes, and Locomotion.* Princeton University Press, Princeton, New Jersey.

Medicine University of China, 1981. *Human Anatomy.* People's Health Press, Beijing.

Mech, C., 1895. Volummessungen des menschlichen Korpers und seiner einzelnen Theile in den verschiedenen Altersstufen. *Zeitschrift fur Biologie* **31:** 125-147.

Miller, D. I., and R. C. Nelson, 1976 (Reprinted). *Biomechanics of Sport.* Henry Kimpton Publishers, London.

Reiss, M. J., 1989. *The allometry of Growth and Reproduction.* Cambridge University Press.

Reynolds, H. M., 1974. *Measurement of the inertial properties of the segments savannah baboon.* Ph.D dissertation. Southern Methodist University.

Ricker, W. E., 1973. Linear regressions in fishery research. *Journal Fisheries Research Board of Canada,* 30: 409-434.

Roebuck, J. A., Kroemer, K. H. E., and Thomson, W. G., 1975. *Engineering Anthropometry Methods.* John Wiley & Sons, New York, London, Sydney, Toronto.

Ross, W. D., and Wilson, B. D., 1973. A somatotype dispersion index. *The Research Quarterly,* 44: 372-374.

Ross, W. D., Drinkwater, D. T., Bailey, D. A., Marshall, G. R., and Leahy, R. M., 1980. Kinanthropometry: Traditions and new Perspectives. In: *Kinanthropometry II,* edited by: Ostyn, M. and Beunen, G., University Park Press, Baltimore.

Santschi, W. R., DuBois, J., and Omoto, C., 1963. *Moments of Inertia and Centre of Gravity of the Living Human Body.* Wright-Patterson Air Force Base, Ohio. AMRL-TRD-63-36.

Shuttleworth, F. K., 1939. The physical and mental growth of girls and boys age six to nineteen in relation to age at maximum growth. *Monographs. Society for Research in Child Development. Volume 4, No. 3.*

Snedecor, G. W., Cochran, W. G., 1967. *Statistical methods.* The Iowa State University Press, Ames, Iowa.

Snyder, R. G., Schneider, L. W., Owing, C. L., Reynolds, H. M., Golomb, D. H., and Schork, M. A., 1977. *Anthropometry of infants, children and youths to age 18 for product safety design.* Society of Automotive Engineers, Warrendale.

Sokal, R. R., Rohlf, F. J., 1981. *Biometry, 2nd edition.* W. H. Freeman and Company, San Francisco.

Sokal, R. R., Rohlf, F. J., 1987. *Introduction to biostatistics, 2nd edition.* W. H. Freeman and Company.

Stijnen, V. V., Willems, E. J., Spaepen, A. J., Peeraer, L., and Van Leemputte, M. 1983. A modified release method for measuring the moment of inertia of the limbs. In: *International Congress of Biomechanics VIII-B,* pp. 1138-1143. eds, Matsui, H. and Kobayashi, K., Human Kinetics, Champaign.

Swearing, J. J., 1962. *Determination of Centre of Gravity of Man.* Federal Aviation Administration, Oklahoma, ASTIA AD-10 410.

Swearing, J. J. and Young, J. W., 1965. *Determination of Centres of Gravity of Children, Sitting and Standing.* Federal Aviation Administration, Oklahoma, 1965. AM 65-23.

Tanner, J. M., 1962. *Growth at Adolescence.* Blackwell Scientific Publications, Oxford.

Tanner, J. M., 1981. *A History of the Study of Human Growth.* Cambridge University Press, Cambridge.

Tanner, J. M. and Whitehouse, R. H., 1966. Standards from birth to maturity for height, weight, height velocity and weight velocity: British children, 1965. *Archives of Disease in Childhood,* **41**: 454.

Tanner, J. M. and Whitehouse, R. H., 1976. Clinical longitudinal standards for height, weight, height velocity, and stages of puberty. *Archives of Disease in Childhood,* **51**: 170-179.

Thompson, H., 1938. Body proportions in the growth infant. *Growth* **2**: 1-12.

Teissier, G., 1948. La relation d'allometrie: sa significance statistique et biologique. *Biometrics* **4**: 14-48.

Vajda, A. S., Borms, J., Duquet, W. and Hebbelinck, M., 1980. Longitudinal dimensional growth patterns of Belgian boys and girls. In: *Kinanthropometry II.* pp.381-389. eds. Ostyn, M. and Beunen, G., University Park Press, Baltimore.

Weinbach, A. P., 1938. Contour maps, centre of gravity, moment of inertia and surface area of the human body. *Human Biology* 10: 356-371.

Weiner, J. S. and Lourie, J. A., 1969. *IBP Handbook No. 9, Human Biology, a Guide to Field Methods.* Blackwell Scientific Publication, Oxford and Edinburgh.

Winter, D. A., 1979. *Biomechanics of Human Movement.* Wiley, New York.

Wong, M. Y., 1989. Likelihood estimation of a linear regression model when both variables have error. *Biometrika,* 76: 141-148.

Yokoi, T., Shibukawa, K., Ae, M., Ishijima, S., and Hashihara, Y., 1985. Body-segment parameters of Japanese children. In: *Biomechanics IX-B,* eds. Winter, D. A., Human Kinetics Publishers, Champaign, Illinois.

Zar, J. H., 1968. Calculation and miscalculation of the allometric equation as a model in biological data. *BioScience,* 18: 1118-1120.

Zatzorski, V. and V. Seluyanov, 1983. The mass and inertia characteristics of the main segments of the human body. In: *Biomechanics VIII-B, Human Kinetics,* pp. 1152-1159. eds. H. Matsui and K. Kabayashi, Champaign.

Zatzorski, V. and V. Seluyanov, 1985. Estimation of the mass and inertia characteristics of the human body by means of the best predictive regression equations. In: *Biomechanics IX-B,* pp.233-239. eds. Winter, D. A. Champaign, IL.

Zook, D. E., 1932. A study by means of water displacement. *American Journal of Diseases of Children* 43: 1347-1432.

APPENDIX I Programme to compute inertial characteristics

```
C       PROGRAMMES TO COMPUTE INERTIAL CHARACTERISTICS
        DIMENSION A(5,40),B(5,40)
        CHARACTER R*5
        WRITE(*,*)'PLEASE ENTER THE DATA FILE NAME:'
        READ(*,16) R
C       INPUT DATA FILE WITH FORMAT
C             NN
C             I1 I2 M
C             L2 V2
C             .....
C             LI1 VI1
C             .....
C             LI2 VI2
C             .....
C             LM VM
      OPEN (1,FILE=R)
      OPEN (2,FILE='ARM',ACCESS='DIRECT',FORM='FORMATTED',RECL=147)
      IZ=0
4     READ(1,*,END=89) NN
      IZ=IZ+1
C     NN: OBSERVATION NUMBER;
C     I1: THE POINT BETWEEN HAND AND FOREARM;
C     I2: THE POINT BETWEEN FOREARM AND UPPER ARM;
C     M: THE MOST PROXIMAL POINT ON UPPER ARM
      READ(1,*) I1,I2,M
      I3=M
      DO 10 I=1,M
10    READ(1,'(F6.1,1X,F6.1)') A(1,I),A(2,I)
      DO 3 I=1, I1
      B(1,I)=A(1,I)
3     B(2,I)=A(2,I)
      CALL CG(1,B,I1,C1,Z1,P1,I1,I2,I3,M)
      IK=I2-I1+1
      DO 5 I=1, IK
      B(1,I)=A(1,I1+I-1)
5     B(2,I)=A(2,I1+I-1)
      CALL CG(2,B,IK,C2,Z2,P2,I1,I2,I3,M)
      IK=I3-I2+1
      DO 6 I=1, IK
      B(1,I)=A(1,I2+I-1)
6     B(2,I)=A(2,I2+I-1)
      CALL CG(3,B,IK,C3,Z3,P3,I1,I2,I3,M)
      IK=I2
      DO 7 I=1, IK
      B(1,I)=A(1,I)
7     B(2,I)=A(2,I)
      CALL CG(4,B,IK,C4,Z4,P4,I1,I2,I3,M)
      IK=I3-I1+1
      DO 8 I=1, IK
      B(1,I)=A(1,I1+I-1)
8     B(2,I)=A(2,I1+I-1)
      CALL CG(5,B,IK,C5,Z5,P5,I1,I2,I3,M)
      IK=I3
      DO 1 I=1, IK
      B(1,I)=A(1,I)
1     B(2,I)=A(2,I)
      CALL CG(6,B,IK,C6,Z6,P6,I1,I2,I3,M)
      C1=C1/(B(1,I1)-B(1,1)) *100
      C2=C2/(B(1,I2)-B(1,I1))*100
      C3=C3/(B(1,I3)-B(1,I2))*100
      C4=C4/(B(1,I2)-B(1,1)) *100
      C5=C5/(B(1,I3)-B(1,I1))*100
      C6=C6/(B(1,I3)-B(1,1)) *100
      Z=A(2,I2)-A(2,I1)
      ZZ=A(2,I3)-A(2,I2)
C     OUTPUT FILE NAMED 'ARM' WITH 23 DATA FOR EACH RECORD:
C     OBSERVATION NO.,
C     CG OF HAND, FOREARM, UPPER ARM, FOREARM WITH HAND,
C     UPPER ARM WITH FOREARM,
```

```
C     TOTAL UPPER LIMB; PMI IN THE SAME SEQUENCE;
C     RG IN THE SAME SEQUENCE,
C     AND VOLUME OF HAND, FOREARM, UPPER ARM, TOTAL UPPER LIMB
      WRITE(2,9,REC=IZ)NN,C1,C2,C3,C4,C5,C6,Z1,Z2,Z3,Z4,Z5,Z6,
     *       P1,P2,P3,P4,P5,P6,A(2,I1),Z,ZZ,A(2,M)
16    FORMAT (A5)
      GO TO 4
9     FORMAT(I3,1X,6F6.2,3X,F6.4,1X,4(F6.2,1X),F6.1,1X,6(F5.2,1X),
     *       F6.1,F7.1,1X,F5.0,1X,F6.0)
89    STOP
      END

      SUBROUTINE CG(ID,A,IK,C,ZI,P,I1,I2,I3,M)
      DIMENSION A(5,40),W(40)
      PARAMETER(PI=3.1415926)
C     SPECIFIC GRAVITY FOR HAND (D1), FOREARM (D2),
C     AND UPPER ARM (D3)
      DATA D1,D2,D3/1.144,1.122,1.081/
      IF(ID.EQ.1) THEN
            DO 221 I=2,IK
            DD=D1
221            CALL SS(A,DD,I,W)
      ELSE IF(ID.EQ.2) THEN
            DO 222 I=2,IK
            DD=D2
222            CALL SS(A,DD,I,W)
      ELSE IF(ID.EQ.3) THEN
            DO 223 I=2,IK
            DD=D3
223            CALL SS(A,DD,I,W)
      ELSE IF(ID.EQ.4) THEN
            DO 224 I=2,IK
            IF(I.LT.I1) THEN
                  DD=D1
                  CALL SS(A,DD,I,W)
            ELSE
                  DD=D2
                  CALL SS(A,DD,I,W)
            ENDIF
224            CONTINUE
      ELSE IF(ID.EQ.5) THEN
            DO 225 I=2,IK
            IP=I2-I1
            IF(I.LE.IP) THEN
                  DD=D2
                  CALL SS(A,DD,I,W)
            ELSE
                  DD=D3
                  CALL SS(A,DD,I,W)
            ENDIF
225            CONTINUE
      ELSE
            DO 226 I=2,IK
            IF(I.LE.I1) THEN
                  DD=D1
                  CALL SS(A,DD,I,W)
            ELSE IF(I.GT.I2) THEN
                  DD=D3
                  CALL SS(A,DD,I,W)
            ELSE
                  DD=D2
                  CALL SS(A,DD,I,W)
           ENDIF
226            CONTINUE
      ENDIF
      C=0.
      D=0.

      DO 220 I=2,IK
      C=C+A(5,I)*A(3,I)*A(4,I)
220      D=D+A(3,I)*A(4,I)
      C=C/D
      CM=C+A(1,1)

      ZI=0.
      DO 101 I=2,IK
      ZI=ZI+W(I)
101   CONTINUE
```

```
      R2M=C*C*D
      ZI0=ZI-R2M
      P=SQRT(ZI0/D)/(A(1,IK)-A(1,1))*100.
      ZI=ZI0/10**8
2     RETURN
      END

      SUBROUTINE SS(A,DD,I,W)
      DIMENSION A(5,40),W(40)
      A(3,I)=A(1,I)-A(1,I-1)
      A(4,I)=(A(2,I)-A(2,I-1))*1000./A(3,I)*DD
      A(5,I)=(A(1,I-1)-A(1,1))+A(3,I)/2.
      RZ=SQRT((A(2,I)-A(2,I-1))*1000./A(3,I)/3.14)
      W(I)=DD*(1./4*RZ**4+RZ**2*A(5,I)**2)*3.14*A(3,I)
      END
```

APPENDIX II Parameters of mechanical model for limbs

RG	CG	$y=k\times z+r_1$		$y=k\times\sqrt{z}+r_1$	
		s	r_1	s	r_1
0.250	0.640	-	-	6.81	0.0051
0.250	0.650	-	-	10.83	0.0116
0.250	0.660	-	-	26.86	0.0066
0.250	0.670	3.59	0.0291	-	-
0.255	0.630	-	-	4.97	0.0093
0.255	0.640	-	-	6.81	0.0186
0.255	0.650	-	-	10.83	0.0162
0.255	0.660	3.20	0.0328	26.86	0.0080
0.255	0.670	3.59	0.0462	-	-
0.260	0.620	-	-	3.91	0.0161
0.260	0.630	-	-	4.97	0.0263
0.260	0.640	-	-	6.81	0.0259
0.260	0.650	2.89	0.0384	10.83	0.0198
0.260	0.660	3.20	0.0520	26.86	0.0092
0.260	0.670	3.59	0.0586	-	-
0.265	0.610	-	-	3.22	0.0254
0.265	0.620	-	-	3.91	0.0352
0.265	0.630	2.40	0.0155	4.97	0.0362
0.265	0.640	2.62	0.0461	6.81	0.0317
0.265	0.650	2.89	0.0592	10.83	0.0229
0.265	0.660	3.20	0.0661	26.86	0.0103
0.265	0.670	3.59	0.0691	-	-
0.270	0.600	-	-	2.73	0.0371
0.270	0.610	-	-	3.22	0.0458
0.270	0.620	2.21	0.0346	3.91	0.0473
0.270	0.630	2.40	0.0561	4.97	0.0440
0.270	0.640	2.62	0.0678	6.81	0.0366
0.270	0.650	2.89	0.0746	10.83	0.0257
0.270	0.660	3.20	0.0778	26.86	0.0114
0.270	0.670	3.59	0.0783	-	-
0.275	0.580	-	-	2.09	0.0343
0.275	0.590	-	-	2.37	0.0512
0.275	0.600	1.90	0.0194	2.73	0.0583
0.275	0.610	2.04	0.0522	3.22	0.0598
0.275	0.620	2.21	0.0681	3.91	0.0571
0.275	0.630	2.40	0.0781	4.97	0.0507
0.275	0.640	2.62	0.0843	6.81	0.0411
0.275	0.650	2.89	0.0875	10.83	0.0282
0.275	0.660	3.20	0.0882	26.86	0.0123
0.275	0.670	3.59	0.0867	-	-
0.280	0.560	-	-	1.67	0.0350
0.280	0.570	-	-	1.86	0.0566
0.280	0.580	1.65	0.0183	2.09	0.0676
0.280	0.590	1.77	0.0529	2.37	0.0728
0.280	0.600	1.90	0.0704	2.73	0.0739
0.280	0.610	2.04	0.0821	3.22	0.0713
0.280	0.620	2.21	0.0902	3.91	0.0656
0.280	0.630	2.40	0.0955	4.97	0.0568
0.280	0.640	2.62	0.0983	6.81	0.0451

0.280	0.650	2.89	0.0990	10.83	0.0306
0.280	0.660	3.20	0.0977	26.86	0.0132
0.280	0.670	3.59	0.0944	-	-
0.285	0.530	-	-	1.27	0.0065
0.285	0.540	-	-	1.38	0.0504
0.285	0.550	-	-	1.52	0.0683
0.285	0.560	1.44	0.0440	1.67	0.0795
0.285	0.570	1.54	0.0643	1.86	0.0863
0.285	0.580	1.65	0.0787	2.09	0.0895
0.285	0.590	1.77	0.0897	2.37	0.0897
0.285	0.600	1.90	0.0980	2.73	0.0869
0.285	0.610	2.04	0.1041	3.22	0.0814
0.285	0.620	2.21	0.1082	3.91	0.0732
0.285	0.630	2.40	0.1104	4.97	0.0624
0.285	0.640	2.62	0.1108	6.81	0.0489
0.285	0.650	2.89	0.1095	10.83	0.0328
0.285	0.660	3.20	0.1064	26.86	0.0141
0.285	0.670	3.59	0.1017	-	-
0.290	0.510	1.06	0.0564	1.08	0.0690
0.290	0.520	1.13	0.0618	1.17	0.0808
0.290	0.530	1.20	0.0697	1.27	0.0906
0.290	0.540	1.27	0.0786	1.38	0.0983
0.290	0.550	1.36	0.0876	1.52	0.1039
0.290	0.560	1.44	0.0961	1.67	0.1073
0.290	0.570	1.54	0.1037	1.86	0.1085
0.290	0.580	1.65	0.1103	2.09	0.1074
0.290	0.590	1.77	0.1157	2.37	0.1040
0.290	0.600	1.90	0.1198	2.73	0.0984
0.290	0.610	2.04	0.1225	3.22	0.0905
0.290	0.620	2.21	0.1238	3.91	0.0802
0.290	0.630	2.40	0.1237	4.97	0.0675
0.290	0.640	2.62	0.1222	6.81	0.0525
0.290	0.650	2.89	0.1191	10.83	0.0350
0.290	0.660	3.20	0.1147	26.86	0.0149
0.290	0.670	3.59	0.1087	-	-
0.295	0.510	1.06	0.1191	1.08	0.1237
0.295	0.520	1.13	0.1187	1.17	0.1262
0.295	0.530	1.20	0.1200	1.27	0.1284
0.295	0.540	1.27	0.1225	1.38	0.1300
0.295	0.550	1.36	0.1257	1.52	0.1305
0.295	0.560	1.44	0.1291	1.67	0.1296
0.295	0.570	1.54	0.1323	1.86	0.1271
0.295	0.580	1.65	0.1351	2.09	0.1229
0.295	0.590	1.77	0.1372	2.37	0.1169
0.295	0.600	1.90	0.1385	2.73	0.1089
0.295	0.610	2.04	0.1387	3.22	0.0989
0.295	0.620	2.21	0.1379	3.91	0.0867
0.295	0.630	2.40	0.1359	4.97	0.0724
0.295	0.640	2.62	0.1327	6.81	0.0559
0.295	0.650	2.89	0.1283	10.83	0.0370
0.295	0.660	3.20	0.1225	26.86	0.0157
0.295	0.670	3.59	0.1153	-	-
0.300	0.510	1.06	0.1592	1.08	0.1613
0.300	0.520	1.13	0.1567	1.17	0.1596
0.300	0.530	1.20	0.1553	1.27	0.1579
0.300	0.540	1.27	0.1549	1.38	0.1558

0.300	0.550	1.36	0.1551	1.52	0.1528
0.300	0.560	1.44	0.1556	1.67	0.1489
0.300	0.570	1.54	0.1561	1.86	0.1436
0.300	0.580	1.65	0.1563	2.09	0.1369
0.300	0.590	1.77	0.1560	2.37	0.1286
0.300	0.600	1.90	0.1552	2.73	0.1186
0.300	0.610	2.04	0.1535	3.22	0.1067
0.300	0.620	2.21	0.1509	3.91	0.0929
0.300	0.630	2.40	0.1473	4.97	0.0771
0.300	0.640	2.62	0.1427	6.81	0.0592
0.300	0.650	2.89	0.1369	10.83	0.0390
0.300	0.660	3.20	0.1299	26.86	0.0165
0.300	0.670	3.59	0.1217	-	-
0.305	0.510	1.06	0.1916	1.08	0.1921
0.305	0.520	1.13	0.1875	1.17	0.1876
0.305	0.530	1.20	0.1844	1.27	0.1831
0.305	0.540	1.27	0.1820	1.38	0.1782
0.305	0.550	1.36	0.1802	1.52	0.1726
0.305	0.560	1.44	0.1786	1.67	0.1662
0.305	0.570	1.54	0.1770	1.86	0.1586
0.305	0.580	1.65	0.1752	2.09	0.1498
0.305	0.590	1.77	0.1731	2.37	0.1395
0.305	0.600	1.90	0.1705	2.73	0.1277
0.305	0.610	2.04	0.1672	3.22	0.1142
0.305	0.620	2.21	0.1631	3.91	0.0988
0.305	0.630	2.40	0.1581	4.97	0.0816
0.305	0.640	2.62	0.1522	6.81	0.0623
0.305	0.650	2.89	0.1452	10.83	0.0409
0.305	0.660	3.20	0.1371	26.86	0.0172
0.305	0.670	3.59	0.1278	-	-
0.310	0.510	1.06	0.2197	1.08	0.2191
0.310	0.520	1.13	0.2144	1.17	0.2124
0.310	0.530	1.20	0.2099	1.27	0.2055
0.310	0.540	1.27	0.2060	1.38	0.1984
0.310	0.550	1.36	0.2025	1.52	0.1907
0.310	0.560	1.44	0.1992	1.67	0.1821
0.310	0.570	1.54	0.1960	1.86	0.1726
0.310	0.580	1.65	0.1926	2.09	0.1619
0.310	0.590	1.77	0.1889	2.37	0.1498
0.310	0.600	1.90	0.1847	2.73	0.1363
0.310	0.610	2.04	0.1800	3.22	0.1213
0.310	0.620	2.21	0.1746	3.91	0.1045
0.310	0.630	2.40	0.1683	4.97	0.0859
0.310	0.640	2.62	0.1612	6.81	0.0654
0.310	0.650	2.89	0.1531	10.83	0.0428
0.310	0.660	3.20	0.1440	26.86	0.0179
0.310	0.670	3.59	0.1338	-	-

APPENDIX III Procedure of data collection and dataset creation

1) Anthropometric data

i. Anthropometric data were collected and recorded on proforma together with a survey number and any personal details of the subject (ie. date of birth, sex, date of measurement, etc.).

ii. A FORTRAN 77 program was written by the author to produce a sub-dataset containing individual data including survey number, sex, decimal age at the date of the survey, somatotype, ratios and anthropometric variables which were to be analysed.

2) Inertial characteristics:

i. Upper limb segments: The data for the hand were taken and recorded in "density" form while the data for the forearm and upper arm were in "distribution" form. These two data subsets were combined into one. The data for each individual subject included the survey number, three numbers representing marks at the wrist, elbow, and shoulder and two columns which represented the distance and the accumulated volume respectively. A FORTRAN 77 program (Appendix I) was written by the author to calculate the inertial properties of each upper limb segment. The output was stored in a formatted file.

ii. Calf: The data were taken and stored in volume distribution form. The inertial properties were calculated with a FORTRAN 77 program written by the author which was similar to that in Appendix I except for the data input and output formats.

iii. Thigh: The data were recorded in three columns. The first column represented the height (distance) of each thigh section, and the other two columns the anteroposterior and transverse lengths of the thigh section in relation to the height. The area of each section was estimated as 0.785 × anteroposterior length × transverse length. The volume was then estimated with the formula given in 2.2.2.1.2 and stored in distribution form. The procedure followed then was the same as processing the calf data.

3) Creation of the dataset

All the four data subsets were then merged into one dataset, with the sequence number distingushing the same individuals in different subsets. The sequence of the variables is the same as that in Table 3.1. The data were stored in a unformatted FORTRAN 77 file.

APPENDIX IV Discribtion of the statistical parameters

1) Sample parameters (Table 3.2)
  i. Sample mean:

$$\bar{x} = \frac{1}{n}\sum_{1}^{n} x_i$$

ii. Sample standard deviation:

$$SD = s = \sqrt{\frac{\sum x^2 - (\sum x)^2 / n}{n-1}}$$

iii. Standard error:

$$S_{\bar{x}} = \frac{s}{\sqrt{n}}$$

iv. Coefficient of variance:

$$CV = \frac{s}{\bar{x}} \times 100$$

2) Statistical tests:
  i. Student's "t" test (Table 3.3, 3.11):

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2(n_1-1) + s_2^2(n_2-1)}{n_1+n_2-2}}\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}}$$

ii. "F" test (Analysis of variation, Table 3.2)

$$F = \frac{s_1^2}{s_2^2}$$

3) Major axis slope:
i. The slope:

$$z = \tan\left(\frac{1}{2}\, arctg \frac{2\sum xy}{\sum x^2 - \sum y^2}\right)$$

ii. The variance of the slope (Wong, 1989):

$$s_z^2 = \frac{t_1 t_2 (z^2+1)^2}{n(t_1 - t_2)^2}$$

where

$$t_1 = \frac{s_x^2 + 2zs_{xy} + z^2 s_y^2}{z^2+1},$$

$$t_2 = \frac{z^2 s_x^2 - 2zs_{xy} + s_y^2}{z^2+1}$$

APPENDIX V Programme to correct means by age

```
      DIMENSION X(0:10),A(0:10),B(0:10),C(0:10),D(0:10),H(0:50)
      DIMENSION AA(0:50),ZL(0:50),ZU(0:50),ZZ(0:50),XX(0:10)
      DIMENSION YY(0:10)
      DATA (XX(J),J=0,8)/8.5,9.,10.,11.,12.,13.,14.,15.,16/
      DATA M/8/
      OPEN(1,FILE='MA.E')
      OPEN(2,FILE='MA.O')
      READ(1,*) Q0
      READ(1,*) (X(J),J=0,M)
      DO 9 IP=4,76
      READ(1,*) Q0
      READ(1,*) (A(J),J=0,M)
      A(M+1)=0.
      DO 8 J=0,M+1
      IF(A(J).EQ.0.) GO TO 7
8     CONTINUE
7     N=J-1
      DO 1 I=0,N-1
1     H(I)=X(I+1)-X(I)
      DO 2 I=1,N-1
      AA(I)=3.*(A(I+1)*H(I-1)-A(I)*(X(I+1)-X(I-1))+A(I-1)*H(I))
     *     /H(I-1)/H(I)
2     CONTINUE
      ZL(0)=1.
      ZU(0)=0.
      ZZ(0)=0.
      DO 3 I=1,N-1
      ZL(I)=2.*(X(I+1)-X(I-1))-H(I-1)*ZU(I-1)
      ZU(I)=H(I)/ZL(I)
3     ZZ(I)=(AA(I)-H(I-1)*ZZ(I-1))/ZL(I)
      ZL(N)=1.
      ZZ(N)=0.
      C(N)=0.
      DO 4 I=N-1,0,-1
      C(I)=ZZ(I)-ZU(I)*C(I+1)
      B(I)=(A(I+1)-A(I))/H(I)-H(I)*(C(I+1)+2.*C(I))/3.
4     D(I)=(C(I+1)-C(I))/3./H(I)
      DO 6 MT=0,8
      DO 21 I1=0,N-1
      PP=X(I1)
      IF((XX(MT).GE.X(I1)).AND.(XX(MT).LT.X(I1+1))) GO TO 22
21    CONTINUE
      I1=I1-1
22     PZ=ABS(XX(MT)-PP)
      ZZP=A(I1)+B(I1)*PZ+C(I1)*PZ**2+D(I1)*PZ**3
6      YY(MT)=ZZP
      WRITE(2,37) IP,(YY(J),J=0,N-1)
37    FORMAT (I3,2X,10(F7.2,1X))
9     CONTINUE
      END
```

APPENDIX VI SAD results and its calculation

1) SAD of paired group means

i. Boy

9	1.07							
10	1.35	0.37						
11	1.93	0.87	0.64					
12	1.20	0.42	0.37	0.83				
13	1.34	0.28	0.24	0.59	0.37			
14	0.71	0.57	0.73	1.31	0.51	0.75		
15	0.92	0.52	0.54	1.17	0.46	0.66	0.33	
16	1.07	0.60	0.51	1.11	0.42	0.66	0.45	0.17
AGE	8	9	10	11	12	13	14	15

ii. Girls

9	0.50					
10	1.45	1.04				
11	1.59	1.14	0.30			
12	1.20	0.79	0.32	0.44		
13	2.25	1.82	0.84	0.70	1.05	
14	1.51	1.05	0.32	0.10	0.37	0.79
AGE	8	9	10	11	12	13

iii. Boys against girls

	0.67	0.67	0.71	0.57	0.59	1.50	1.42
AGE	8	9	10	11	12	13	14

2) About the calculation of the SAD

Carter *et al* (1983) demonstrated the calculation of SAD and its derived parameters, SAM, S_A^2 and the formula for "t" test. They used the original data of the three somatotype components to calculate the parameters so that the formulae were complicated and give the impression that the SAD can provide more information than the three separate components.

However, by an examination of these formulae, it was found by the present author that most of the parameters Carter and others designed represent the combination of the parameters of the individual components (except for the SAM, which may be replaced by ΣSAD^2, rather than ΣSAD, as had been defined). No raw data are needed for the statistics of SAD, as the sample statistics for the individual components will yield everything that the SAD system does.

Formulae are given here which will achieve this. In order to make the expression easier, x, y, z are used to represent the three somatotype components.

$$S_A^2 = s_x^2 + s_y^2 + s_z^2$$

$$\sum SAD^2 = (n-1)(s_x^2 + s_y^2 + s_z^2)$$

Additionally, the "t" formula derived by Carter and others is not correctly expressed. Their $\overline{S}$ is apparently a vector, and as the result, their "t" formula produces a three-dimension-vector and not a scalar quantity as it should do. Here, $|\overline{S}_1 - \overline{S}_2|$ should have been used instead.

There are also some statistical errors in this paper. In the "F" test used for testing equality of variance, the authors consistently wrongly counted the first degree of freedom of the "F" ratio. Furthermore, it appears that the authors did not appreciate the basic relationship that $F_{(1,n)} = t^2_{(n)}$. As a result, a number of unnecessary calculations and statements were made.

In conclusion, from these examples and the discussion in 4.2.6, the author of this thesis believes, that the SAD system, both its construction, and its algorithms, need further improvements.