Journal of Sports Sciences, 1994, **12**, 235–242

Morphological prototypes, assessment and change in elite athletes

MICHAEL R. HAWES* and DANIELA SOVAK

Human Performance Laboratory, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada

Accepted 17 November 1992

The concept of a morphological prototype in relation to the development of athletes is examined from the standpoint of the kinanthropometric techniques available to the sport scientist. Examples of the utility of the morphological prototype in the context of modern-day sport are provided in a variety of winter and summer sports. Somatotypes drawn from competitors at the 1988 Olympic and 1991 World Junior Speed Skating Championships are presented representing the somatotypic prototype. Statement of the prototype in variables that are both discrete and sensitive to change over the short term is considered to be more appropriate for evaluating the progress of young athletes. Examples drawn from speed skating, figure skating, swimming and synchronized swimming are used to illustrate changes and differences in muscle mass, skinfold corrected muscle diameters, bone mass and sum of skinfolds. The concept of establishing an individual ideal prototype through optimizing morphological variables is introduced.

Keywords: Somatotype, anthropometry, kinanthropometry.

Introduction

It is evident to astute observers that body form and dimension varies between athletes and non-athletes, that athletes competing in different sports very often have different physiques, and that athletes performing at different levels in the same sport may have similar morphological traits but differ in the extent of their expression. Such assessments may be drawn from cursory empirical observations. A greater challenge to the kinanthropometrist, however, is the comprehensive *in vivo* quantification of morphology that will allow definitive analysis of physique, the establishment of the relationship of physique to performance in particular sports and an understanding of the response of specific tissues to the training process.

The morphological prototype is a well-established concept in sport science; nevertheless, it is appropriate to offer a definition of the term at the outset. 'Morphology' is the science of structure and form without regard to function. It is a fundamental law of biology, however, that form follows function and clearly there is a close relationship between the two. Carter (1985) quoted Thompson (1966) as suggesting that 'morphology is not only the study of material things, but has its dynamical aspect, under which we deal with the interpretation, in terms of force, of the operations of energy'. The implication of this statement is that morphology is dynamic in the sense that morphology is related to both the physiology and biomechanics of humans in motion and the recognition that masses, levers and forces are 'the cornerstone of human movement and their quantification is the foundation for building a more complete knowledge of human performance' (Carter, 1985).

A prototype is something that is original, of which copies, imitations, improved forms and representations may be made. Thus, a morphological prototype is a structure which, at any given time, is regarded as fulfilling a purpose well but which will be dynamic in the sense that it will change over the course of time as a result of the interaction of many factors. In the past several decades, incredible changes in sport performance have occurred, as recorded in faster times, greater distances and increased number of rotations. These have occurred as a result of more sophisticated training methods, new techniques, better equipment and facilities, and greater attention to the athlete support systems (coaches, psychologists, therapists, sport scientists). As sport has evolved,

---

* To whom all correspondence should be addressed.

Table 1 Studies of Olympic athletes

			No. of athletes tested						
City	Year	Reference	Males	Females	Total	Total Olympians	Percent studied	Sports tested	Number of medallists
St. Moritz	1928[a]	Muelly (1928)	140	—	140	363	38.57	4	—
Amsterdam	1928	Kohlrausch (1930)	300	30	330	2971	11.11	9	—
London	1948	Cureton (1951)	—	—	45	4062	1.11	3	—
Rome	1960	Correnti and Zauli (1964)	—	—	194	5396	3.60	2	34
Rome	1960	Tanner (1964)	—	—	137	5396	2.54	1	—
Tokyo	1964	Azuma (1964)	—	—	1110	5586	19.87	—	—
Mexico City	1968	de Garay *et al.* (1974)	1117	148	1265	6084	19.09	13	120
Mexico City	1968	di Prampero *et al.* (1970)	116	—	116	6084	1.75	13	2
Munich	1972	Jungmann (1976)	—	—	449	10088	4.45	—	—
Munich	1972	Novak *et al.* (1977)	80	20	100	10088	0.99	7	—
Montreal	1976	Carter *et al.* (1982)	309	148	457	6189	7.38	20	24
Calgary	1988[a]	Hawes and Sovak (1991)	50	30	80	1750	4.57	2	14

[a] Olympic Winter Games.

so the morphological prototype associated with specific sports has changed and become more clearly etched. Examples include the changing form of female figure skaters – smaller, lighter, less body fat, more muscular – in response to the development of the technical demands of the sport.

The prototype may be defined in many contexts, by age, sex, level of performance, sport and so on. The usefulness of a morphological prototype may be to assist the understanding of human variance and the plasticity of morphological characteristics; to act as an indicator of changes occurring in a specific sport and hence serve as a model for guiding the development of those coming after; or as a tool for identifying individuals with exceptionally well-suited morphological characteristics for a given sport. The idea is an attractive one and many descriptive studies of the morphology of athletes (Tittel and Wutscherk, 1972, cited over 100 and Carter, 1985, estimated a further 100+ since that review) have been published with the intent of satisfying one or more of the above purposes. The most notable among these studies are the series of classical works reporting on the structure of Olympic athletes (Table 1). Studies of athletes competing at the 1928, 1948, 1960–72 and 1976 Summer Olympic Games have been published (Kohlrausch, 1930; Cureton, 1951; Correnti and Zauli, 1964; Tanner, 1964; Azuma, 1964; de Garay *et al.*, 1974; Jungmann, 1976; Novak *et al.*, 1977; Hirata, 1979a, b; Carter *et al.*, 1982). In addition, two studies of competitors at the 1924 and 1988 Winter Olympic Games have been reported (Muelly, 1928; Hawes and Sovak, 1991). Numerous studies have also reported upon the morphological characteristics of competitors at World Championships, major international games and championships and national teams in preparation for major events.

The task for an applied kinanthropometrist is to synthesize the vast quantity of published information describing the morphology of many of the best athletes in the world and translate that information into meaningful concepts which may be used in the long-term development of young athletes. Deriving relevant information from published studies is often confounded by inconsistent techniques and measurement protocols resulting in incomplete or limited information. Many of these problems have been addressed in recent years as more sophisticated techniques and methods of handling data become available to sport scientists. Most studies still rely upon the traditional methods of anthropometry. It may be that we are on the verge of very rapid change in methodology as medical imaging techniques such as magnetic resonance imaging (MRI), computerized axial tomography (CAT), ultrasound and other techniques are being explored for more precise *in vivo* quantification of the human structure. These methods require rigorous attention to ethical considerations and their technical validity. Regardless of the progress made in sophisticated technology, strict adherence to specified technique is a prerequisite for any work to have utility. Several standards have been set in the field of anthropometry, including the International Biological Programme (Weiner and Lourie, 1969), the reference text of Martin and Saller (1957) and the standards recognized by the International Society for the Advancement of Kinanthropometry (Ross and Marfell-Jones, 1982). Secondary procedures for comprehensive analysis of anthropometric parameters include techniques of describing somatotype, body composition and proportionality analysis.

Profiling by somatotype

Somatotype is by definition a gestalt of human form without regard to size. It is the examination of the relative

Table 2 Comparison of medallists, non-medallists, sprint and distance skaters at the 1991 World Junior Speed Skating Championships and the 1988 Winter Olympic Games

	Endomorphy	Mesomorphy	Ectomorphy
Males			
Top 3 medallists WOGAP ($n=9$)	2.2±0.30	4.6±0.94	2.4±0.80
Non-medallists WOGAP ($n=36$)	2.3±0.62	4.8±0.67	2.2±0.63
Top 3 medallists WOGAP sprint ($n=4$)	2.2±0.40	5.0±1.06	1.9±0.72
Top 3 medallists WOGAP distance ($n=4$)	2.2±0.22	4.2±0.67	2.9±0.63
Top 3 medallists WJSSC ($n=5$)	2.2±0.40	4.3±0.96	3.0±0.96
Non-medallists WJSSC ($n=24$)	2.5±0.53	4.6±0.57	2.6±0.60
Top 3 medallists WJSSC sprint ($n=3$)	2.0±0.41	3.8±1.06	3.5±0.84
Top 3 medallists WJSSC distance ($n=4$)	2.1±0.38	4.1±1.07	3.2±1.01
Females			
Top 3 medallists WOGAP ($n=5$)	2.4±0.53[a]	4.0±0.16	2.3±0.18
Non-medallists WOGAP ($n=23$)	3.1±1.04	3.4±1.00	2.3±0.67
Top 3 medallists WOGAP sprint ($n=3$)	2.0±0.39	4.0±0.21	2.3±0.24
Top 3 medallists WOGAP distance ($n=2$)	2.6±0.38	4.0±0.07	2.3±0.10
Top 3 medallists WJSSC ($n=5$)	3.2±0.43[a]	3.8±0.32	2.3±0.54
Non-medallists WJSSC ($n=19$)	3.8±1.23	3.9±0.93	2.3±0.96
Top 3 medallists WJSSC sprint ($n=3$)	3.3±0.45	3.9±0.22	2.2±0.57
Top 3 medallists WJSSC distance ($n=3$)	3.1±0.34	3.9±0.45	2.1±0.82

WOGAP, Winter Olympic Games 1988; WJSSC, World Junior Speed Skating Championships 1991.
[a] Significant difference ($P<0.05$).

proportion of adiposity, musculoskeletal development and the distribution of the latter two components in space (relative linearity). Ross (pers. comm., International Kinanthropometry Project, Burnaby, Canada, 1990) has described it as a taxonomy of human form. The most prevalent method of somatotyping is that of Heath and Carter (1967), which has become the *de facto* method for this type of analysis within the area of sport science. It has the advantages of a quantitative approach and recognizes that it represents phenotype at one moment in time. The Heath–Carter somatotype is an excellent choice for describing and comparing morphological prototypes. Our laboratory has been able to assess competitors in speed skating at the 1988 Olympic Winter Games (Sovak and Hawes, 1990; Hawes and Sovak, 1991). Subsequently, we have been able to assess competitors at the 1991 World Junior Speed Skating Championships.

As an example of somatotypic prototypes, we have examined the most successful competitors (top three) and compared them to the non-medallists at both competitive levels (Table 2). There are small differences in the endomorphic component, which is more obvious in the female competitors than the male competitors. The more successful men at both levels of competition appear to be more linear and less muscular than their cohorts. Women at the junior level display no differences in the mesomorphic and ectomorphic components, but at the senior level the more successful women have a considerably larger mesomorphic component than the non-medallists. Comparison of the most successful (top three) speed skating athletes at the junior and senior levels shows that the difference between the male competitors lies mostly within the ectomorphic component, while differences between the levels of female competitors lie mostly within the endomorphic component. Comparison of somatotype between the most successful competitors in the sprint and endurance events is inconclusive at the junior level for males. As one would expect, the successful male competitors in the Olympic sprint events tended to be more mesomorphic than the successful endurance competitors. Within the women's events, there appears to be no definitive differences between the successful competitors in the sprint and endurance events at either level of competition.

The somatotype is a ready measure for comparing individuals and groups of athletes which may be construed as a prototype. Carter (1985) suggested that the somatotype may also be a useful tool for assisting in the identification of young talent. While the somatotype may indeed be one of several guidelines considered in the selection of young talent, it is clearly not intended as a measure for monitoring the short-term effects of training upon body form and composition.

Anthropometric models

If a morphological prototype is to be employed as a model with practical applications for the development of young athletes, the prototype must be stated in variables which are both discrete and sensitive to change over the short term and which are appropriate for the anticipated changes. While medical imaging technology is developing very rapidly, its cost and availability is prohibitive for most applications within sport. Nevertheless, geometric and arithmetic models and equations have been developed over the past two decades which permit a partitioning of the human body into its main tissues and which allow the discrete examination of tissues at specific sites. While the absolute values calculated may be imprecise, when used over the long term the change in value provides important information to the sport scientist and through him/her to the coach and athlete.

Profiling of muscle mass and distribution

The description of *in vivo* body composition has enjoyed lively debate for an extended period of time. For decades body composition implied the estimation of fat and fat-free mass despite the logic of the early work of Matiegka (1921), who attempted to apportion the body into specific tissue compartments. More recent work by Clarys *et al.* (1984), Martin (1984) and Drinkwater (1984) has firmly re-established the original direction and concept of Matiegka's work. In 1990, Martin *et al.* published equations for the estimation of muscle mass in men based on cadaver evidence. Data from six unembalmed cadavers were used to derive a regression equation to predict total muscle mass. Martin *et al.* (1990) subsequently validated this equation by predicting the known muscle masses from five embalmed cadavers ($r^2 = 0.93$, S.E.E. = 1.58 kg) and compared the results with estimates derived from the equations of Matiegka (1921) and Heymsfield *et al.* (1982). The equation recommended by Martin and co-workers was much better able to predict muscle mass than the other two equations, which substantially underestimated the muscle mass of what must be regarded as a limited sample. Martin *et al.* (1990) attempted to minimize the specificity of their equation by ensuring that the upper and lower body was represented in the three circumference terms. They commented that the usefulness of knowledge of predicted muscle mass is surely as useful a tool in both sport and clinical practice as knowledge of amount of subcutaneous adipose tissue.

The inclusion of an estimation of muscle mass has been a standard practice in longitudinal assessment of high-performance athletes in our laboratory. Its usefulness may be illustrated by examination of two swimmers in contention for a place on the 1988 Olympic team (Sovak and Hawes, 1989). Individual profiles had been established over an extended period (Table 3). In both cases, body weight had increased slightly, reflecting increased muscle mass as subcutaneous adipose (Σ10Skf) diminished. As the vital selection meet approached, one swimmer started to lose body weight which was seen to occur in both muscle mass and subcutaneous adipose tissue. In retrospect, and confirmed by lactate analysis, this swimmer had reached a point of overtraining where his body was unable to recuperate from the training process. This vitally important information was identified as a result of profile analysis using relatively simple equipment and technique.

The specificity of training is a well-recognized principle in sport. It follows that more discrete information about status and change in quantity at specific muscle locations may be required in order to monitor changes resulting from the training process. The cross-sectional area of muscle is directly related to potential for force output (Ikai and Fukunaga, 1968); therefore, an examination of dimensions that represent cross-sectional area should be included in the athlete's profile so as to monitor training status. The approach of Matiegka (1921), which has subsequently been employed by many others, has been to measure limb girths and skinfold thicknesses over the girths and geometrically derive the diameter of muscle (+ bone) by assuming that the limb is circular and the adipose tissue is evenly distributed around the limb. A recent master's thesis (Anderson, 1991) examined the efficacy of these assumptions using cadaver specimens.

Table 3 Body composition changes of two male swimmers observed over a 15 month training period

	March 1987	April 1988	July 1988
Swimmer A			
Body mass (kg)	63.0	66.3	67.0
Σ10Skf (mm)	121.2	80.8	79.6
Muscle mass (kg)	24.9	29.4	29.1
Swimmer B			
Body mass (kg)	71.2	73.1	70.5
Σ10Skf (mm)	81.7	62.6	54.6
Muscle mass (kg)	32.4	33.1	31.7

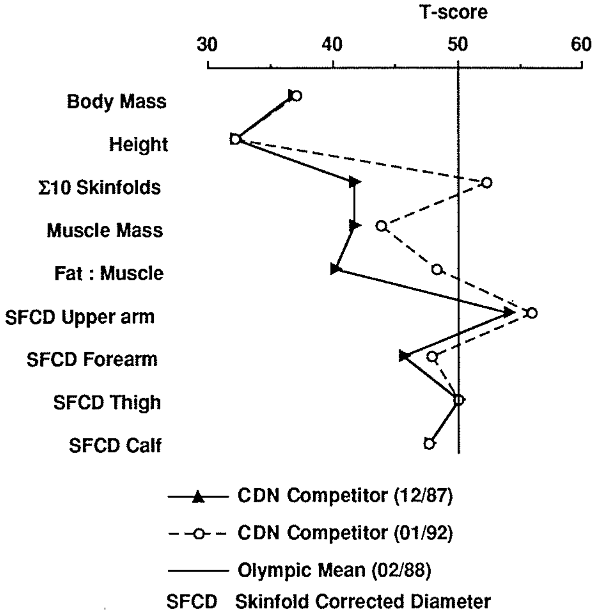

Figure 1 Morphological profile of a male international calibre speed skater.

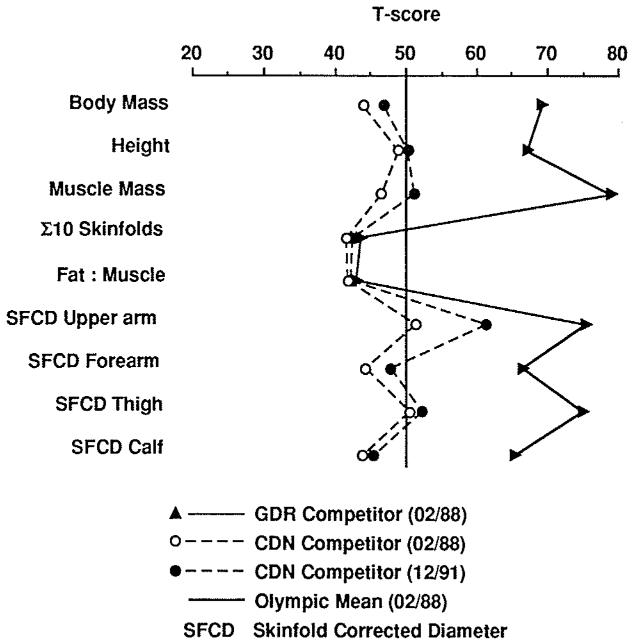

Figure 2 Comparison of a female Olympic speed skating medallist with a top Canadian performer.

Girth and corresponding skinfolds were measured at the mid-upper arm, maximum forearm, mid-thigh and maximum calf sites. The limbs were subsequently sectioned at each site, photographed and tissue borders were digitized in order to determine circumference. Geometric modelling was used to predict the circumference of the muscle + bone tissue. A correlation value of $r = 0.936$ was obtained when the directly measured and geometric estimates were compared. A systematic difference ($<5.0\%$) was found between the two data sets, which was attributed in part to the convoluted muscle found in two of the three cadavers. Examination of MRI scans of healthy young adults suggests that the convoluted margin was not typical of healthy tissue and likely contributed to the discrepancy between estimated and measured circumference.

A prototype description of total muscle mass and skinfold corrected muscle diameter at specific sites can be an extremely valuable tool in moulding a developing athlete. Two examples illustrate this concept of a morphological prototype. In the first case, a male speed skater of international calibre had a corrected diameter profile similar to the most successful speed skaters in the world (Fig. 1). The fact that this individual was not in Olympic medal contention in 1988 was therefore more likely the result of shortcomings in psychological preparation, technique or cardiovascular training. The training emphasis for this athlete in the intervening years has been to maintain muscle mass, as evidenced by skinfold corrected diameters, with greater emphasis in training placed upon other areas of perceived weaknesses.

The second sample is a Canadian female speed skater who finished in the top six in her event in 1988. Examination of her profile (Fig. 2) shows substantial differences, particularly in proportionate muscle mass, which is specified in the corrected diameter values, from the most successful athlete in her event (Sovak and Hawes, 1990). Thus the emphasis for this athlete in the intervening years between Olympiads has been to increase muscle mass. This has occurred, although greater improvements are seen in her upper body measures when in fact the most dramatic differences in the original analysis were seen in the lower body sites.

Profiling of bone mass

The skeleton is a dynamic tissue responding to environmental stresses by remodelling its shape and increasing or decreasing its density. Nevertheless, it is less volatile than either muscle or adipose tissue and its influence upon human performance has been largely neglected. Matiegka (1921) proposed that skeletal mass could be estimated from an equation that included stature, the maximum diameter of the humerus, wrist, femur and ankle, and a constant. Drinkwater *et al.* (1984) attempted to validate the proposed equation against recent cadaver data and found that an adjustment to Matiegka's constant produced a more accurate estimate in their sample of older persons. Drinkwater *et al.* (1984) made the comment, however, that the true value of the coefficient probably lies between the original and their calculated value. An estimation of bone mass within a prototypical

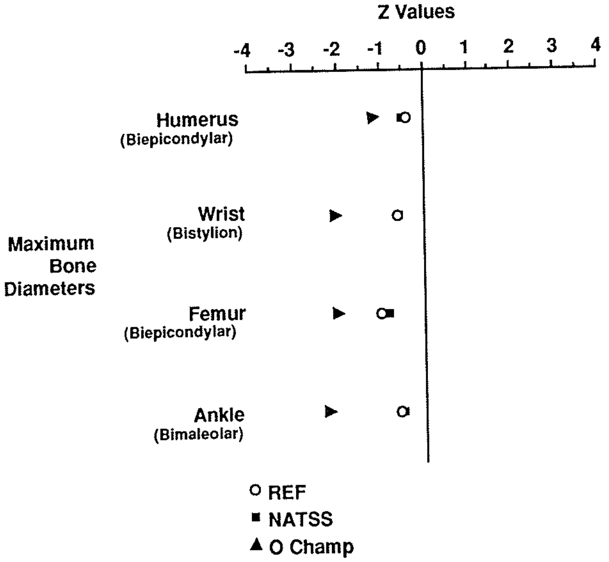

Figure 3 Phantom z-values for bone diameters of Olympic (O Champ), national calibre synchronized swimmers (NATSS) and a reference sample (REF).

model may provide insight into structural factors which may contribute to athletic success. In a longitudinal study of high-performance synchronized swimmers, Hawes and Sovak (1990) found that the World and Olympic champion had disproportionately narrow bony diameters compared with other synchronized swimmers competing at the international level (Fig. 3). Since positive buoyancy contributes to the ease of performing exercises above water, relatively small mass of the most dense body tissue could certainly be construed as a morphological advantage in athletes of otherwise equal abilities. A relatively delicate skeletal frame may be considered a selection factor in the identification of young athletes in this sport. Roby *et al.* (1989) have shown evidence that bone density in successful synchronized swimmers may also be less than established norms, thereby contributing to positive buoyancy.

Profiling of adipose tissue mass and distribution

Estimation of the adipose tissue compartment of the human body has been a contentious issue for many years. The standard for estimation of body fatness has been established through the principle of densitometry. The use of skinfold calipers for estimating proportionate adiposity has been validated against the densitometric standard. It has become increasingly clear in the last decade that the limitations of the densitometric methods expressed by the early protagonists of this method have been ignored. Lohman's (1981) review of over 100 skinfold equations and Martin's (1985) eloquent review of the inherent assumptions in the measurement of skinfold thicknesses by calipers cast serious doubts upon the efficacy of these methods. The expression of proportionate adiposity has limited value within a prototypical model as an absolute number to strive for unless a sufficient number of skinfold sites is included in the equation to reduce the limitations of fat patterning and adjustment is made for age and sex. Examination of the arithmetic sum of skinfold thicknesses and values at individual sites is a more realistic evaluation of adiposity.

A female provincial calibre figure skater aged 14.9 years provides an example of a profile that uses the arithmetic sum of skinfold thicknesses in addition to estimated muscle mass and skinfold corrected diameters (Table 4). Initially, the athlete showed a profile of 86.3 mm for the sum of 10 skinfolds (Σ10Skf), which is average when compared with mean values of provincial team skaters, and a relatively high value of 43% muscle distributed in greater proportion to the upper body when compared with the same group.

A coaching decision was made to concentrate on skill development with the expectation that this would cause a redistribution of muscle mass to the thigh and particularly the calf. Eight months later, small increases in Σ10Skf and muscle mass were observed but most significantly muscle had been redistributed from the upper arm to the thigh and calf as indicated by the skinfold corrected diameters. Three months later, the athlete had further gained weight partly as a result of an increment in stature (1.5 cm), but also as a result of increased Σ10Skf values (102.6 mm). Although nutritional counselling was advised at this point, the skater waited 5 months before availing herself of this service. An initial 7 day dietary recall revealed that she was consuming about 4300 kcal (18 000 kJ)/day, while 2700 kcal (11 302 kJ)/day was recommended by a dietitian for a girl of her age and activity level. The latest assessment in January 1992 (Table 4) indicates that she has reduced Σ10Skf (78.3 mm) and increased muscle mass, particularly in the vital area of the calf, with the result that there has been a marked improvement in jumping height. A follow-up dietary assessment revealed that she had reduced her caloric intake to 2500 kcal (10 465 kJ)/day.

Optimizing profiles

It is simplistic to consider that more muscle and less fat will always enhance performance. It is evident in many sports that a compromise between adiposity and muscularity must be struck for optimal morphological condition. To this end, Sovak *et al.* (1990) have examined the relationship between muscularity and adiposity at times of optimal performance in athletes studied on a longitudinal basis. An optimal performance is considered to be a

Table 4 Morphological profile of a provincial calibre female figure skater

	June 1990	February 1991	May 1991	October 1991	January 1992
Age (years)	14.9	15.5	15.8	16.2	16.4
Body mass (kg)	53.0	55.3	56.2	56.1	53.0
Height (cm)	160.3	160.4	161.9	162.3	161.8
Σ10Skf (mm)	86.3	92.2	102.6	97.5	78.3
Muscle (%)	42.8	42.0	41.7	42.8	45.3
CDU (cm)	7.1	6.9	6.9	6.9	6.8
CDF (cm)	6.8	6.8	6.8	6.8	6.8
CDT (cm)	14.0	14.5	14.5	14.6	14.6
CDC (cm)	9.5	9.7	9.5	9.8	10.1

CDU, CDF, CDT and CDC are skinfold corrected diameters of the upper arm, forearm, thigh and calf, respectively.

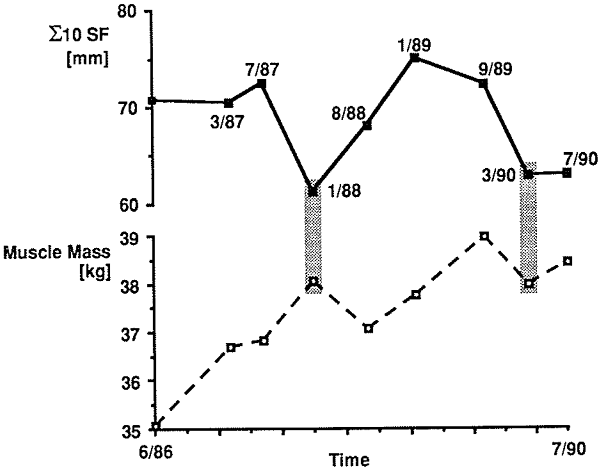

Figure 4 Estimated muscle mass and Σ10Skf over a 4 year period for a male swimmer in relation to his world record performances (1/88 and 3/90) (Sovak and Hawes, 1990).

major championship or world record. The objective is to recognize optimal physical condition and to be able to reproduce this condition in a particular athlete at subsequent major championships. Figure 4 shows the estimated quantities of muscle and Σ10Skf over a 4 year period for a world-class swimmer who has held world best and world record times. On the occasion of recording these times, it may be seen that the swimmer was at his lowest values for Σ10Skf and slightly below his maximum values for estimated muscle mass. This would suggest optimal rather than maximal conditioning.

Conclusions

It may be argued that the influence of physical training on body structure is small by comparison with the range of genetic variation. It is also evident that human performance is a multivariate phenomenon; other factors such as physiological condition, biomechanical factors, psychological state, physical environment and the sociocultural context will affect performance. Structure is but one small part of the total performance matrix. As performances at the highest levels improve, the magnitude of improvement is measured in smaller and smaller increments. Thus attention to the detail of all elements in the performance matrix becomes of increasing significance. In this sense, the attention to the detail of morphological preparation may make the difference between winning and losing when all other factors are equated.

The morphological profile of an individual measured against him or herself or against a profile representing an ideal of the very best performers in a particular sport is a useful tool in the arsenal of the coach and sport scientist. It provides a model against which improvement may be measured and an ideal to strive for. The concept may be used to monitor the training effect on individual athletes, recognize the morphological limitations or advantages to skill performance, motivate during times when other quantitative measures of improvement are lacking and determine optimal condition.

Acknowledgements

This work has been supported by the Canadian Fitness and Lifestyle Research Institute, Sport Canada, Alberta Sport Council, Olympic Oval High Performance Fund and the University of Calgary. The authors would like to acknowledge the substantial contributions of Kate Plant, Sheila Vanaanen, Robert Heinemeyer and Dale Oldham.

References

Anderson, P. (1991). Measurement of discrete tissue parameters using ultrasound, segment zone anthropometry and biochemical analysis validated against cadaver evidence. MSc Thesis, University of Calgary.

Azuma, T. (1964). *Olympic Medical Archives.* Report of the Japanese Olympic Medical Archives Committee, Tokyo.

Carter, J.E.L. (1985). Morphological factors limiting human performance. In *Limits of Human Performance* (edited by D.H. Clarke and H.M. Eckert), pp. 106–117. American Academy of Physical Education Papers No. 18. Champaign, IL: Human Kinetics.

Carter, J.E.L., Ross, W.D., Aubrey, S.P., Hebbelinck, M. and Borms, J. (1982). Anthropometry of Montreal Olympic athletes. In *Physical Structure of Olympic Athletes* (edited by J.E.L. Carter), pp. 25–51. Basel: Karger.

Clarys, J.P., Martin, A.D. and Drinkwater, D.T. (1984). Gross tissue weights in the human body by cadaver dissection. *Human Biology*, **56**, 459–473.

Correnti, V. and Zauli, B. (1964). *Olimpionici 1960*. Roma: Marves.

Cureton, T.K., Jr (1951). *Physical Fitness of Champion Athletes*. Urbana, IL: University of Illinois Press.

de Garay, A.L., Levine, L. and Carter, J.E.L. (1974). *Genetic and Anthropological Studies of Olympic Athletes*. New York: Academic Press.

di Prampero, P.E., Pinero Limas, F. and Sassi, G. (1970). Maximum muscular power, aerobic and anaerobic, in the 116 athletes performing at the XIXth Olympic Games in Mexico. *Ergonomics*, **13**, 665–674.

Drinkwater, D.T. (1984). An anatomically derived method for the anthropometric estimation of human body composition. PhD Thesis, Simon Fraser University.

Drinkwater, D.T., Martin, A.D., Ross, W.D. and Clarys, J.P. (1984). Validation by cadaver dissection of Matiegka's equations for the anthropometric estimation of anatomical body composition in adult humans. In *Perspectives in Kinanthropometry* (edited by J.A.P. Day), pp. 221–227. Champaign, IL: Human Kinetics.

Hawes, M.R. and Sovak, D. (1990). Skeletal ruggedness as a factor in performance of Olympic and national calibre synchronized swimmers. *Journal of Sports Sciences*, **8**, 163–164 (abstract).

Hawes, M.R. and Sovak, D. (1991). The 1988 Winter Olympic Games Anthropometry Project. *New Horizons in Human Movement: Proceedings of the 1988 Seoul Olympic Scientific Congress*, Dankook University, Korea.

Heath, B.H. and Carter, J.E.L. (1967). A modified somatotype method. *American Journal of Physical Anthropology*, **27**, 57–64.

Heymsfield, S.B., McManus, C., Smith, J., Stevens, V. and Nixon, D.W. (1982). Revised equation for calculating bone free arm muscle area. *American Journal of Clinical Nutrition*, **36**, 680–690.

Hirata, K.I. (1979a). *Selection of Olympic Champions*, Vol. I. Toyota: Chukyo University.

Hirata, K.I. (1979b). *Selection of Olympic Champions*, Vol. II. Toyota: Chukyo University.

Ikai, M. and Fukunaga, T. (1968). Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. *Internationale Zeitscheift für Angewandte Physiologie*, **26**, 26–32.

Jungmann, H. (1976). *Sportwissenschaftliche Untersuchungen wahrend der XX. Olympischen Spiele, Munchen 1972*. Grafelfing: Demeter.

Kohlrausch, W. (1930). Zusammenhange von Korperform und Leistung. Ergebnisse der anthropometrischen Messungen an den Athleten der Amsterdamer Olympiade. *Arbeitsphysiologie*, **2**, 187–204.

Lohman, T.G. (1981). Skinfolds and body density and their relationship to body fatness: A review. *Human Biology*, **53**, 181–225.

Martin, A.D. (1984). An anatomical basis for assessing human body composition: Evidence from 25 dissections. PhD Thesis, Simon Fraser University.

Martin, A.D. (1985). Prediction of body fat by skinfold caliper: Assumptions and cadaver evidence. *International Journal of Obesity*, **9**, 31–39 (suppl. 1).

Martin, A.D., Spenst, L.F., Drinkwater, D.T. and Clarys, J.P. (1990) Anthropometric estimation of muscle mass in men. *Medicine and Science in Sports and Exercise*, **22**, 729–733.

Martin, R. and Saller, K. (1957). *Lehrbuch der Anthropologie*, Vol. 1. Stuttgart: Fischer.

Matiegka, J. (1921). The testing of physical fitness. *American Journal of Physical Anthropology*, **4**, 223–230.

Muelly, K. (1928). Die Form des Korpers als Ausdruck seiner Funktion. In *Die Sportarztlichen Ergebnisse der II. Olympischen Winterspiele in St. Moritz 1928* (edited by W. Knoll). Berne: Verlag Paul Haupt.

Novak, L.P., Woodward, W.A., Bestit, C. and Mellerowicz, H. (1977). Working capacity, body composition and anthropometry of Olympic female athletes. *Journal of Sports Medicine and Physical Fitness*, **17**, 275–283.

Roby, F.B., Atwater, A.E., Going, S.B., Lohman, T.G., Puhl, J.L. and Tucker, M. (1989). Bone mineral content in synchronised swimmers. In *Proceedings of the First IOC World Congress on Sport Sciences*, pp. 198–199, Colorado Springs.

Ross, W.D. and Marfell-Jones, M.J. (1982). Kinanthropometry. In *Physiological Testing of the Elite Athlete* (edited by J.D. MacDougall, H.A. Wenger and H.J. Green), pp. 75–115. Ottawa: CASS.

Sovak, D. and Hawes, M.R. (1989). Changes in active tissue development of 10 elite male swimmers during 14 months of training prior to Olympic trials. In *Proceedings of the First IOC World Congress on Sports Sciences*, p. 55, Colorado Springs.

Sovak, D. and Hawes, M.R. (1990). Distinguishing anthropological factors in female speed skaters with respect to their success in the 1988 Winter Olympic Games. *Journal of Sports Sciences*, **8**, 177–178 (abstract).

Sovak, D., Hawes, M.R. and Smith, D. (1990). Anthropological status of a world record holding swimmer: A four year longitudinal study. Presented at the *VIth International Symposium on the Biomechanics and Medicine in Swimming*, Liverpool, September.

Tanner, J.M. (1964). *The Physique of the Olympic Athlete*. London: Allen and Unwin.

Thompson, D.W. (1966). *On Growth and Form* (abridged edition by J.T. Bonner). Cambridge: Cambridge University Press.

Tittel, K. and Wutscherk, H. (1972). *Sportanthropometrie*. Leipzig: Barth.

Weiner, J.S. and Lourie, J.A. (1969). *Human Biology: A Guide to Field Methods*. IBP Handbook No. 9. Oxford: Blackwell.