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Anthropometry: the individual and the population

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CLAIRE C. GORDON AND KARL E. FRIEDL

Military anthropometry in the United States has a long history, beginning at least as early as the Civil War, when such variables as stature, weight, and the body mass index (BMI) were utilized to identify recruits likely to be malnourished, tuberculous, or otherwise unfit for military duty (Ordronaux, 1863). The Civil War surveys also encouraged extensive investigation of the relationships between anthropometry and ancestry, birthplace, physiological measures, disease prevalence, and physical anomalies (Gould, 1869; Baxter, 1875). During World War I (WWI), stature, weight, BMI, pubic height, and chest circumference were utilized as indicators of fitness for load-carrying, marching, and fighting (Davenport & Love, 1921). Indeed, the nature and validity of relations between anthropometry and soldier health and physical performance continue to be a primary focus of military research, and they form the basis of many anthropometric standards for the selection and retention of individual military personnel (Friedl, 1992).

Whereas anthropometric standards for accession, retention, and occupational assignment are by nature applied to the individual soldier, it is the anthropometric variation of military populations as a whole that must be considered in the design and sizing of clothing, protective equipment, workstations, and other military hardware. The first US military survey to specifically address clothing sizing was conducted on approximately 100 000 separatees (soldiers discharged from service) at the end of WWI (Davenport & Love, 1921). By the end of World War II (WWII), gross incompatibilities between body size distributions and the workstations of major military hardware systems (such as the gun turrets of the B-17 bomber aircraft) had fuelled the application of anthropometry in the ever-growing field of human engineering (Brues, 1992). Periodic anthropometric surveys of US military personnel have been undertaken ever since (see Table 12.1). Concise historical overviews of these are provided by Churchill & McConville (1976) and White (1978); comprehensive descriptions of post-WWII research are available in Air Force (Robinette & Fowler, 1988) and Army (Bell, Donelson & Wolfson, 1991) annotated bibliographies.

Table 12.1. *Anthropometric surveys of US military populations*

Year	Sample	Population	Source
1861–65	1 232 256	volunteers	Gould (1869)
1863–65	501 068	draftees	Baxter (1875)
1971–18	1 961 692	draftees	Davenport & Love (1921)
1919	103 909	separatees	Davenport & Love (1921)
1946	105 062	Army men	Newman & White (1951)
1946	8 859	Army women	Randall & Munro (1949)
1950	4 063	Air Force flyers	Hertzberg *et al.* (1954)
1964	1 549	Navy flyers	Gifford *et al.* (1965)
1966	6 682	Army men	White & Churchill (1971)
1966	2 008	Marines	White & Churchill (1978)
1967	2 420	Air Force flyers	Grunhofer & Kroh (1975)
1968	1 905	Air Force women	Clauser *et al.* (1972)
1970	1 482	Army Aviators	Churchill *et al.* (1971)
1977	1 331	Army women	Churchill *et al.* (1977)
1988	5 506	Army men	Gordon *et al.* (1989)
1988	3 491	Army women	Gordon *et al.* (1989)

Why 'military' anthropometry?

The application of anthropometry to fitness and human engineering problems is not necessarily unique to the military. However, military populations themselves are unique since they are neither biological populations nor random samples of the biological populations represented in the US and its territories. Recruiting strategies interact with a host of sociological variables such as socioeconomic status, education, and social attitudes to influence those who 'immigrate' into the military. Regulations governing body size, occupational assignment, and career progression further influence military age, gender, and height–weight distributions. Thus, studies of anthropometric variation over time and space, and relationships between anthropometric variables and measures of health and performance, must address complex interactions between biological and social factors that influence the dependent variables of interest. In fact, the distributions of such demographic variables as age, gender, and race are so influential in determining anthropometric distributions that demographic shifts alone can render an anthropometric database obsolete (Bradtmiller, Rhatnaparkhi & Tebbetts, 1986; Gordon *et al.*, 1989), and may be more important than the secular trends of individual biological populations in that regard (Greiner & Gordon, 1990).

Other aspects of military anthropometry are also unique. Because research results are implemented in military regulations and/or materiel (equipment) specifications that directly affect the safety, performance, and careers of large numbers of individuals, measurement validity, reliability and precision are crucial. Measurement validity is determined by the closeness of the approximation between the anthropometric variable and the epidemiological or engineering factor it represents in the application at hand. Crotch height, for example, is valid for clothing design but inappropriate as a substitute for trochanteric height in a man-model or functional leg length in a workstation design. Regrettably, many classical anthropometric dimensions are simply not valid for military application, making standardization of measurement techniques with academia difficult despite significant efforts such as the Airlie Consensus Conference (Lohman, Roche & Martorell, 1988). Because a dimension appropriate for one military application may be invalid in another, multipurpose military surveys have of necessity included large numbers of dimensions, and these have been carefully selected and meticulously defined to enhance their validity for military applications (Clauser *et al.*, 1986a,b).

Relatively stringent controls on data reliability and parameter estimate precision are also required, owing to the unique role of military anthropometry in military policy-making, specifications, and regulations. Data reliability is enhanced through extensive landmarking (drawing anatomical landmarks on the body using surgical markers), frequent test–retest, and on-site computerized data entry and editing (Clauser *et al.*, 1988; Churchill, Bradtmiller & Gordon, 1988; Gordon & Bradtmiller, 1992). Parameter estimate precision is ensured through 'worst case' power calculations for relevant statistics and relatively complex sampling strategies and subject acquisition procedures to ensure that demographic and occupational subgroups are appropriately represented (Gordon *et al.*, 1989). The prohibitive cost of these large sample sizes has led military anthropologists to explore a variety of alternatives to random and stratified random sampling for certain applications (Churchill & McConville, 1976). Demographically and/or anthropometrically matched subsamples of existing databases are also utilized to limit the need for new data collection (Bradtmiller, McConville & Clauser, 1985; Annis & McConville, 1990b).

Table 12.2. *Height standards for military accessions*

Service	Males	Females
USA	60–80 in	58–80 in
USAF	60–80 in	58–80 in
USN	60–78 in	58–78 in
USMC	60–78 in	58–78 in

NHANES II (Najjar & Rowland, 1987) 1st–99th percentiles: 62.6 – 75.6 in (males); 57.6 – 69.7 in (females).

Military anthropometry and the individual: personnel selection

Anthropometry is used intensively in military personnel selection for accession, retention, and occupational training. In general, height restrictions are intended primarily to exclude unusually large or small individuals for whom protective equipment will be difficult to obtain; occupation-specific restrictions ensure equipment compatibility for hardware systems with limited accommodation potential; and weight-for-height and percentage body fat restrictions are applied to ensure acceptable levels of fitness.

Accession standards

The current US Army height standards are: 60–80 inches for men (152.4–203.2 cm) and 58–80 in for women (147.3–203.2 cm), but even these standards can be waived (AR 40-501, 1989). As can be seen in Table 12.2, the height limits are similar for the three main services, but the Marine Corps has a more restrictive upper height limit (72 in; 182.9 cm) for women. Comparison with NHANESII data (Najjar & Rowland, 1987) suggests that none of these standards eliminates more than 2% of the civilian population.

Accession standards for the services also include weight–height and/or body fat restrictions. For most of this century, weight standards were used by the US military to exclude underweight men, but this application reversed with the use of weight standards for weight control, following public criticism in the mid-1970s that military personnel tended to be overly fat and appeared to be unprepared to defend the nation (Friedl, 1992). Body weight standards were then established which screened for overweight instead of underweight using weight-for-height limits that approximated a body mass index (wt/ht^2) maximum (Laurence, 1988).

Until 1991, restrictive weight standards for women excluded 29% of the general population from entering the US Army (based on the NHANESII data), while only 3% of males were excluded. Based on a medical definition of overweight (at 120% of the young population average), few women allowed to enlist were overweight but a considerable portion of men were (Laurence, 1988). In a 1983 sample, these overweight men were found to have a significantly higher rate of attrition from the military, for reasons other than enforcement of weight standards. Men who were underweight (under 80% of the population average) also had a higher attrition rate, producing a U-shaped curve for 36-month attrition. Buddin (1989) later found that changes in Army basic training attenuated the higher attrition of overweight men, although it still remained higher than average. Buddin (1989) also found that lax enforcement of the weight entry standards allowed many women 5–10 lb (2.3–4.5 kg) above their standard to enter the Army anyway, and that these women did not demonstrate a higher attrition rate. More recently, in a large sample of US Army recruits followed through basic training and the first six months after basic training, overweight women were found to have a lower attrition than the 'within standards' weight women when body fat was equal (Friedl *et al.*, 1989).

At the upper ranges of body mass index, men show a decrease in aerobic capacity but an increase in lift capacity compared with the average (Fig. 12.1). A similar relationship exists for women. Thus, absolute weight standards tend to exclude some of the strongest individuals and suggest a serious flaw in military selection since various studies have demonstrated that the majority of military tasks involve lifting and carrying (Robertson & Trent, 1985; Vogel *et al.*, 1980). In the same data set, body fat has no correlation with lift capacity, suggesting that a body fat standard would not inadvertently eliminate strong individuals from the military.

Because the use of weight or BMI alone discriminated against well-muscled individuals, the weight regulations were not rigorously enforced and it was left to the subjective assessment of a physician to determine if an overweight soldier was also obese. President Carter asked for research and recommendations to improve the fitness and long-range health of the military (Department of Defense, 1981). This led to a 1983 directive that all services would use circumference-based anthropometric regression equations to estimate body fat, as the US Marines were already doing (Wright, Dotson & Davis, 1980, 1981). Regression-estimated percentage body fat thus replaced subjective assessments, with recommended standards of 20 and 26% body fat for men and women, respectively.

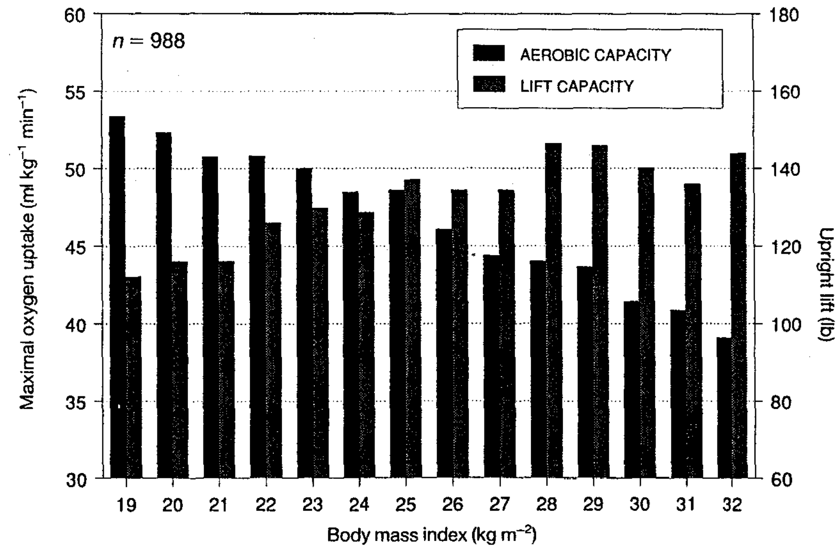

Fig. 12.1. The relationship between body mass index, aerobic capacity, and lift capacity for 988 Army males.

Since 1983, the services have each continued to modify their entry standards; the US Navy and Army now include body fat measures in their exclusion criteria. Based upon the 1989 study by Friedl and colleagues, which reports individual success of men and women in achieving their retention standards six months after the end of basic training, the Army allows male accessions 4% body fat over the retention standards to which they will be later held; Army accession standards for women are the same as retention standards.

Retention standards

Retention standards require that every individual on military active duty be weighed and/or measured for body fat at least once per year to ensure that they fall below the prescribed upper limits of percentage body fat. Individuals not meeting these standards are given a first-time opportunity to come within standards, and subsequent failures to meet the standards culminate in elimination from the military. As can be seen in Table 12.3, each of the services set different fat standards in relation to their own objectives for military appearance, health considerations, and physical fitness requirements. However, the ultimate goal of each and the driving force behind the Department of Defense Directive mandating a weight

Table 12.3. *Relative fat limits (%) for US military*

Males	USAF	USA	USN	USMC
17–20 yrs	20	20	26	18
21–27 yrs	20	22	26	18
28–29 yrs	20	24	26	18
30–39 yrs	26	24	26	18
40+ yrs	26	26	26	18
Females				
17–20 yrs	28	30	36	26
21–27 yrs	28	32	36	26
28–29 yrs	28	34	36	26
30–39 yrs	34	34	36	26
40+ yrs	34	36	36	26

control programme for all services is to discourage overeating and encourage exercise (Kryswicki, Consolazio & Johnson, 1970).

The services have also developed different predictive equations, which are presented in Table 12.4. These have been periodically revised since 1983; three sets of male and female circumference equations are currently in use. Each of these equations is based on studies of US Military populations, with a best-fit multiple regression analysis to determine which of the most convenient and reproducible anthropometric measurements in the hands of lay observers are the best predictors of body fat measured by hydrostatic weighing. The striking similarity of the three male equations, in contrast to the disparity between female equations, reinforces the perception that male body fat is relatively well predicted by an abdominal girth, while the greater variety of fat sites available in women makes standardization of predictive equations rather more difficult (Vogel & Friedl, 1992).

Methods which are technically more sophisticated than circumference measurements have been repeatedly proposed for adoption by the military. So far, however, no *expedient* method has surfaced which substantially improves upon anthropometric estimations of fatness. Standards based upon body circumferences also correlate well with the objectives of the military services' weight control programmes. Abdominal circumference, for example, is the primary offender of military appearance, the primary site of excess fat deposition in overfed and underexercised individuals, and the site most associated with adverse health risks (Larsson *et al.*, 1984; Terry *et al.*, 1991). Used in the

Table 12.4. *Predictive equations currently in use by US military*

All measurements are in cm and kg; abd1 is defined at the natural waist; abd2 is defined at the navel.

US Air Force and Navy[2]

men: density = $(-0.191 \times \log[\text{abd2-neck}]) + (0.155 \times \log[\text{height}]) + 1.032$.
$n = 602$; $r = 0.90$, see = 3.52.

women: density = $(-0.350 \times \log[\text{abd1 + hip-neck}]) + (0.221 \times \log[\text{height}]) + 1.296$.
$n = 214$, $r = 0.85$, see = 3.72

US Army[2]

men: % fat = $(76.5 \times \log[\text{abd2-neck}]) - (68.7 \times \log[\text{height}]) + 43.7$.
$n = 1126$, $r = 0.82$, see = 4.02.

women: % fat = $(105.3 \times \log[\text{weight}]) - (0.200 \times \text{wrist}) - (0.533 \times \text{neck}) - (1.574 \times \text{forearm}) + (0.173 \times \text{hip}) - (0.515 \times \text{height}) - 35.6$.
$n = 266$, $r = 0.82$, see = 3.60.

US Marine Corps[3]

men: % fat = $(0.740 \times \text{abd2}) - (1.249 \times \text{neck}) + 40.985$.
$n = 279$, $r = 0.81$, see = 3.67.

women: % fat = $(1.051 \times \text{biceps}) - (1.522 \times \text{forearm}) - (0.879 \times \text{neck}) + (0.326 \times \text{abd2}) + (0.597 \times \text{thigh}) + 0.707$.
$n = 181$, $r = 0.73$, see = 4.11.

[1]Hogdon & Beckett, 1984a,b; % body fat = $100 \times (4.95/\text{density} - 4.50)$.
[2]Vogel *et al.* (1988).
[3]Wright, Dotson & Davis (1980, 1981).

dichotomous determination of who is or is not maintaining a fit appearance and a reasonable level of physical fitness, the circumferential estimations of body fat provide a suitable screening tool (Hodgdon, Fitzgerald & Vogel, 1990; Conway, Cronan & Peterson, 1989).

Ongoing research for soldier selection

Current approaches to identification of overfat service members rely on the reference method of hydrostatic weighing. Individuals with large body mass, those who perform regular intensive weight-bearing exercise, and Black Americans are likely to be underestimated for body fat because of the assumptions implicit in this method; other groups may be overestimated. The resulting anthropometric equations may be none the less equitable estimates of body fat because they are independent of bone mass, and particularly if they are initially developed from test populations for which the assumptions for hydrostatically determined body fat are generally valid (Friedl & Vogel, 1991). However, ethnic and racial differences in regional fat distribution would be expected to affect anthropometric equations, especially the female equations, which involve estimation of more than one principal site of fat deposition (Seidell *et al.*, 1990; Zillikens & Conway, 1990; Vogel & Friedl, 1992). Studies are currently under way which re-examine the current equations across a range of body sizes and across the three principal racial or ethnic groups represented in the US Army: Blacks, Hispanics, and non-Hispanic Whites. These are being compared to a four-compartment model of fat estimation which includes hydrostatic weighing, total body water, and bone mineral measurements (Friedl *et al.*, 1992).

Since the predictive equations for body fat are used to follow individuals for success in achieving their fat standards within a relatively short period of time (3–18 months, depending on the service), the equations are currently under evaluation for their ability to predict small changes in fatness. An Army–Navy collaborative study will attempt to establish a single anthropometric equation for all military services which suitably classifies fatness in women before and after eight weeks of exercise-induced fat weight loss, taking into account objective measures of aerobic fitness, strength, and health status.

Another improvement in soldier selection standards under consideration is anthropometrically based assessment of fat-free mass to ensure the adequacy of muscular strength of future male and female recruits. Minimum standards of weight or fat-free weight could be effectively tabled against maximum allowances of body fat so that greater relative body fat is allowed for individuals with greater amounts of metabolically more active fat-free mass. Additional research into the development of such a standard is required.

Occupational assignment

In addition to standards for accession and retention, certain military occupations have unique anthropometric standards to ensure full compatibility with available military hardware and/or unique military duties. Table 12.5 summarizes prevailing occupation-specific anthropometric restrictions for the US Army.

Equipment compatibility is the most common reason for anthropometric restriction, and aircraft-specific restrictions on pilot anthropometry are a classic example of this. Safe operation of aircraft requires that the pilot have appropriate 'over the nose' visual field, proper canopy and ejection path clearances, and functional reach capability for all hand- and foot-operated controls. In practice, the design of cockpit geometries that provide wide ranges of multivariate accommodation is difficult. Furthermore, since low vertical profiles are needed to minimize wind drag and battlefield detectability, engineering trade-offs are likely to result in

Table 12.5. *Occupation-specific anthropometric standards*

Occupation	Restrictions	Justification
Diver	Height: 66–76 in (168–193 cm)	Limited size range for diving suits
Pilot	Crotch height: ≥75 cm Span: ≥164 cm Sitting height: ≥102 cm Weight: ≤230 lb (104 kg)	Workspace limitations
MANPADS/PMS Crew member	Height: ≥64 in (162 cm)	Must carry Stinger missile
Military police	Height: ≥68 in (173 cm) (men) ≥64 in (162 cm) (women)	Body size larger than population average
Tank crewman (M48–M60, M1)	Height: ≥73 in (185 cm)	Workspace limitations

Sources: AR 40-501 (1989) and AR 611-201 (1990).

Table 12.6. *Anthropometric standards for military aviators*

	Restrictions
USAF	
Flying Class II	Height: 64–76 in (162–193 cm)
Flying trainees	Height: 64–76 in (162–193 cm) Sitting height: 34–39 in (86–99 cm)
USA	
General	Crotch height ≥75 cm Span ≥164 cm Sitting height ≤102 cm Weight ≤230 lb (104 kg)
OV1 Mohawk	Weight ≤220 lb (100 kg)
OH58 Kiowa	Sitting height ≤95 cm
USN	
General	Height: men ≥62 in (157 cm) women ≥ 58 in (147 cm) Sitting height: 32–41 in (81–104 cm) Buttock–leg length: 36–50 in (91–127 cm) Buttock–knee length: 22–28 in (56–71 cm) Functional reach ≥28 in (71 cm)
Aircraft with ejection seats	Weight: 132–218 lb (60–99 kg)

Sources: Chase (1990); NR 15-34 (1991); AFR 160-43 (1987).

limited workstation space, and it is likely that anthropometric restrictions on military pilots and armoured vehicle crews will continue in the foreseeable future.

Table 12.6 summarizes anthropometric restrictions on US military aviators. Differences in pilot restrictions among the services arise because different aircraft often have different anthropometric accommodation ranges and because there are different philosophies regarding the training of individuals who may fit some, but not all, of the aircraft in their service's inventory. Research to identify the anthropometric limitations of contemporary aircraft continues in all three US services and their allies (Schopper & Cote, 1984; Cote & Schopper, 1984; Schopper, 1986; Turner, 1986; Rose & Erickson, 1988; Farr & Buescher, 1989; Rothwell & Pigeau, 1990; G. F. Zehner, personal communication), although there is considerable debate regarding the best application of such information. Retrofits of aircraft (physical modification of in-service aircraft) are prohibitively expensive, but extensive anthropometric restrictions may also be unacceptable, particularly if reasonable percentages of the female

population are to be accommodated (see Advisory Group for Aerospace Research and Development, 1990, for discussion).

Anthropometric restriction to ensure adequate occupational performance is much less common in the US military, primarily because of the relatively weak relations between body dimensions and objective measures of performance such as strength and endurance (Ayoub & Mital, 1989). At present, the only occupation in which anthropometric standards relate to anticipated performance is military police. Height minima for Army military police are set at approximately 1 in (2.5 cm) above the male and female means so that they will appear larger than most soldiers in crowd control situations. An earlier standard setting a minimum height of 66 in (167.6 cm) and minimum weight of 149 lb (67.7 kg) for firefighters is in the process of being rescinded. The Army concluded that few individuals can hold the large fire hoses alone, regardless of body size, and the restriction unnecessarily excludes most women.

Military anthropometry and the population: materiel system design and sizing

The anthropometric distributions of military populations play a central role in the development and fielding of their materiel (clothing and equipment) systems. Anthropometry influences everything from dress uniforms to boots, body armour, respirators, backpacks, field kitchens, tentage, and the crewstation geometries of jeeps, submarines, helicopters, and tactical aircraft. In general, military designers attempt to accommodate the largest percentage of soldiers possible within standard sizing systems and workstation adjustabilities. The goal for clothing and individual equipment is to achieve maximum accommodation with the fewest sizes possible in order to simplify military logistics and cost to the taxpayer. For military transportation and weapons systems the goal is maximum accommodation with minimum workstation space and weight in order to optimize fuel efficiency, increase speed, and minimize detectability by radar or other surveillance techniques. As will be apparent in the discussions below, the constant need to optimize fit and accommodation while minimizing cost, space, and weight has driven military anthropologists to utilize relatively sophisticated statistical methods in their applications of anthropometry.

Materiel system specifications

All military systems begin their development with a 'requirements document' that describes the system and provides performance specifi-

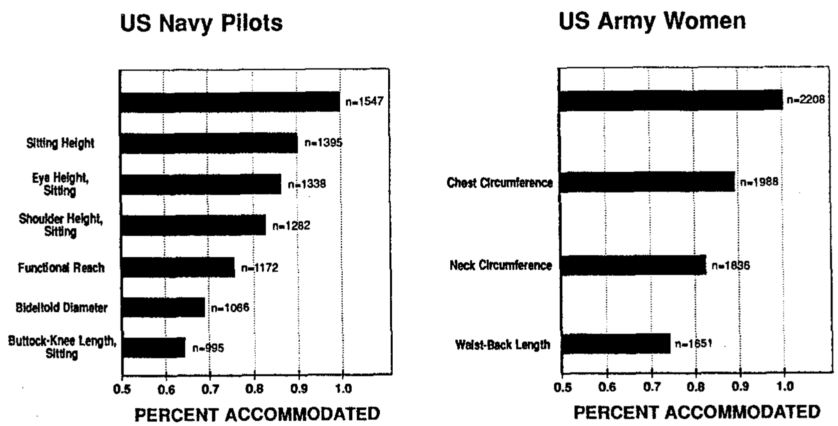

Fig. 12.2. Sequential reduction in population accommodation with simultaneous 5th–95th percentile accommodation requirements for multiple dimensions.

cations that must be met for its intended implementation. Initial specifications for systems with human interfaces state the body size range(s) over which a system must be operative, and thus indirectly determine the percentage of the user population that will be accommodated. Traditionally, such 'accommodation requirements' take the form of a boilerplate line such as 'must accommodate the 5th through 95th percentile soldier', and their intent is to provide operational support for the central 90% of the military population without customized fitting. Unfortunately such simple language leaves in doubt which body dimensions are to be accommodated across the 5th–95th percentile range, and implies the existence of mythical people whose body dimensions are all 5th percentile or all 95th percentile, at either end of the range to be accommodated (Churchill, 1978; Robinette & McConville, 1981; Annis & McConville, 1990a).

Furthermore, although accommodation of 90% of the population is the goal, simultaneous 5th–95th percentile accommodation for more than one dimension inevitably leads to less than 90% overall accommodation because body dimensions are not perfectly correlated with one another (Moroney and Smith, 1972). Figure 12.2 illustrates this problem. With three key sizing dimensions for a dress shirt, simultaneous 5th–95th percentile ranges capture only 75% of the Army female population; with six key crewstation dimensions, simultaneous 5th–95th percentile ranges capture only 64% of the Naval aviator population (Moroney & Smith, 1972). In general, the rate of multivariate accommodation degradation

varies as a function of the correlations between body dimensions, and considerable US and allied military research has focused on computerized estimation of multivariate accommodation rates (Bittner, 1976; Hendy, 1990; Rothwell & Pigeau, 1990). Percentile-based specifications are particularly problematic in workstation applications because these geometries are usually determined by at least four or five anthropometric dimensions that may be poorly correlated with one another, and because the most extreme cases for accommodation may not be uniformly the largest and smallest for all their dimensions, but rather combinations of large and small extremes (Roebuck, Kroemer & Thomson, 1975; Bittner *et al.*, 1987; Hendy, 1990; Zehner, Meindl & Hudson, 1992).

In order to ensure that the extreme values used to specify accommodation requirements result in the intended rates of accommodation, both the Navy and Air Force have explicitly discouraged the use of percentiles in specifications (Arnoff, 1987; Zehner *et al.*, 1992), and the most recent update to MIL-STD-1472D (1991), *Human Engineering Design Criteria for Military Systems*, carries a strong caution against the use of univariate percentiles when more than one key design dimension is involved. Instead, it is recommended that principal components (PC) analysis be applied to reduce the dimensionality of the multivariate space; then the anthropometric data are plotted in the new PC space and a 90, 95, or 98% accommodation circle (2 components) or sphere/ellipsoid (3 compartments) is fitted to the target population (Robinson, Robinette & Zehner, 1992; Meindl, Zehner & Hudson, 1993). Mid-quadrant points on this accommodation surface (see Fig. 12.3) represent the extreme body sizes and proportions present in the population, and these are transformed back into percentiles or actual population values for each extreme case.

The results of such multivariate analyses can be included in specifications as matrices of 'test cases' and subsequently input as government-furnished parameters for computerized man-models and design aids. The dimensionality of the multivariate space, and therefore the number of extreme cases required in each specification, varies with the number and diversity of body dimensions that are considered critical to the design and is thus somewhat subjective. The CADRE manikin series includes 17 cases (Bittner *et al.*, 1987), whereas the United States Air Force (USAF) workstation series contains either 8 or 14 depending upon the number of body dimensions to be specified (Zehner *et al.*, 1992). The assumption underlying these procedures is that accommodation of extreme body proportions on the surface of the multivariate accommodation envelope will ensure accommodation for all those in the population who are less extreme (Meindl *et al.*, 1993).

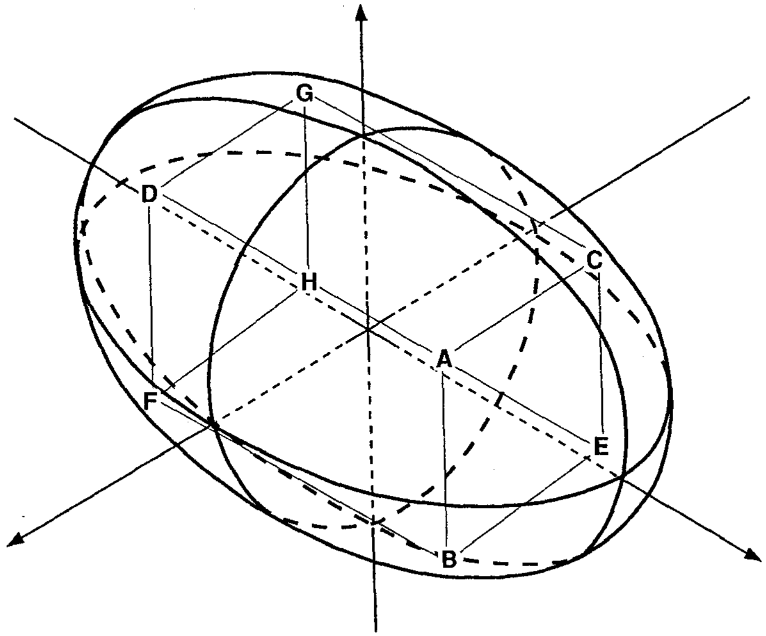

Fig. 12.3. Mid-quadrant points on a three-dimensional accommodation surface (after Fig. 3. in Meindl *et al.*, 1993).

Anthropometric sizing of clothing and individual equipment

Anthropometric data are routinely utilized in the sizing of clothing and individual equipment (CIE) in all three services. The universal goal in military sizing is to meet the accommodation requirement with the fewest number of sizes possible while maintaining a quality of fit that maximizes safety and performance. Although individual services take slightly different approaches in achieving this goal, they share a common, well-established process that involves five fundamental steps: (i) selection of key sizing dimensions for labelling and issuing the item; (ii) determination of the number of sizes needed to accommodate the target population, and the anthropometric limits for each size category; (iii) calculation of nude design values to be used in drafting and grading patterns or moulds for each size category; (iv) creation of prototype garments and verification of garment proportions and limits of fit using military test subjects; and (v) estimation of the population proportions falling into each size category in the system (McConville, 1978; McConville, Robinette & White, 1981).

All anthropometric sizing presupposes the availability of a database

that includes the required body dimensions, measured on a sample of individuals that is representative of the target population. In practice, anthropometric surveys are so costly that representative databases are often constructed from existing ones by stratified random sampling in which age, gender, race, and sometimes height and weight distributions in the target group are matched (Bradtmiller *et al.*, 1985; Gordon *et al.*, 1989; Annis & McConville, 1990b).

With an appropriate database in hand, garment design and purpose are used to determine which dimensions are critical to functional fit and to select one or two key dimensions for sizing and issuing. Key sizing dimensions should sort the user population into subgroups whose members are similar to one another in those body dimensions most important to garment fit and function. Usually, correlation coefficients or principal components analysis are used to identify promising key dimensions, and these can be compared for efficiency using the average 'within-size standard deviation (SZ-SD)' as a measure of within-size homogeneity for critical body dimensions (Gordon, 1986; Robinette & Annis, 1986). Good key dimensions are highly correlated with other dimensions critical to garment fit and have relatively low SZ-SDs for these as well. In practice, military sizing systems rarely utilize more than two key dimensions, owing to the geometric progression in number of sizes that ensues (Roebuck *et al.*, 1975); often, the statistically optimum key dimension is not selected because its reliability is too low for implementation by non-specialists who may be issuing equipment. In most sizing systems, one dimension is selected to control linear variation and a second dimension controls circumferential variation.

After key dimensions are selected, the number of sizes needed to meet the accommodation requirements is determined. Obviously with more sizes in a sizing system, the within-size variation for critical body dimensions will be smaller, and a better garment fit will be possible. However, one rapidly reaches a point beyond which increasing the number of sizes does not substantially reduce body size variability within size categories. This is usually visible on plots of the SZ-SD against number of sizes, given fixed accommodation limits. In practice, garment design and function greatly influence the magnitude of acceptable within-size variation, and often the SZ-SDs of successful sizing systems for similar garment types are used as guidelines.

Once a sizing system structure such as that in Fig. 12.4 is outlined, nude design values for each size category are calculated for all critical body dimensions. Design values are used by the clothing designer or engineer for creating the patterns, models, or moulds used to manufacture the

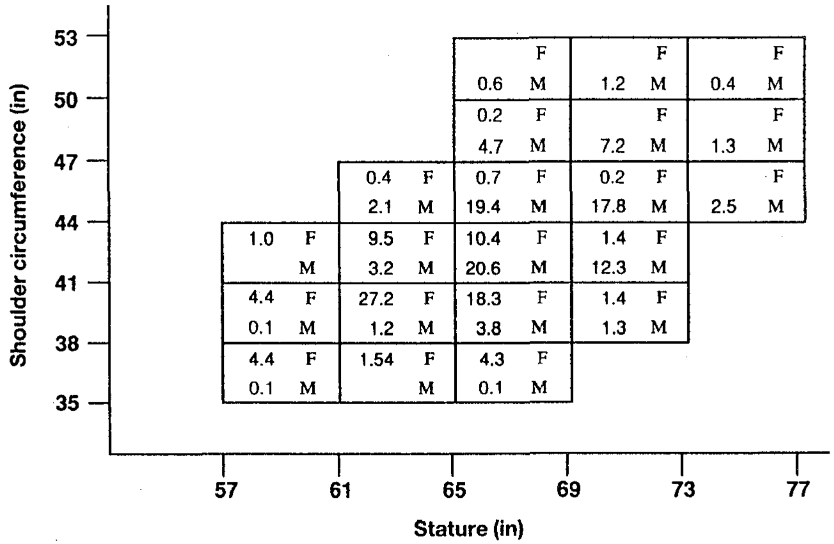

Fig. 12.4. Anthropometric sizing for a US Army field coat. F, percentage of females; M, percentage of males.

developmental item. Multiple regressions using key dimensions as independent variables and critical dimensions as dependent variables are ordinarily used to generate design values because regression estimates can be combined without distorting normal body proportions (McConville & Churchill, 1976; Robinette & McConville, 1981). Depending upon the snugness of fit desired, one can design for mid-size individuals by entering mid-size key dimension values in the regression, design for the largest individuals by regressing on the maximum within-size values of the key dimensions, or design to various extremes by regressing on mid-size values and adding or subtracting multiples of the average within-size standard deviation or standard error of the estimate (Robinette & Annis, 1986; Robinette, Mellian & Ervin, 1990). Statistics calculated directly from size category subgroups are rarely used to set design values because anthropometric variables are not usually normally distributed within size subgroups (McConville *et al.*, 1981).

Using anthropometric design values, master patterns are drafted for a size category near the centre of the sizing system, prototypes are made, and a small-scale fitting trial is conducted to verify master pattern proportions. When master pattern dimensions are finalized, the pattern is graded into other sizes and lengths in the system, usually using a computerized pattern grading system. Dimensional increments ('grade rules') between sizes and lengths are a simple matter to calculate either as

the difference in design values for adjacent categories or more directly as the product of regression slopes and key dimension differences between size categories. Prototype garments are then made for a full-scale fitting trial involving substantial numbers of subjects in all size categories. Full-scale fitting trials permit fine tuning of grade rules and verify the limits of fit for each size category before the garments are subjected to operational trials in the field.

The methods used in generating nude design values for pattern drafting and model or mould making are really a specialized case of creating proportional man-models. Thus anthropometric design values can also be used in specifications for dressforms and manikins so that clothing designers can drape as well as draft patterns, and they are quite compatible with the latest in computer-aided design and computer-aided pattern grading technologies. Mathematical man-models based upon height–weight regressions are also used to generate specifications for the external dimensions of ejection 'dummies' used in biodynamic simulations and testing of escape systems (Tri-Service Aeromedical Research Panel, 1988).

The estimation of population proportions for each size category, commonly called 'tariffing', is the final step in the anthropometric sizing process. Population proportions are ordinarily estimated by sorting an appropriate anthropometric database using the key dimension limits for each size category. Tariffs indicate the relative frequency with which each size category should be purchased; they are ordinarily estimated for males and females separately (see Figure 12.4) and subsequently weighted according to the prevailing gender ratio in the target population. Tariffs are used by military procurement officials to structure multimillion-dollar contracts with civilian garment manufacturers, by stock managers at the Central Initial Issue Facilities supplying major training centres, and by supply sergeants at the individual unit level.

Whereas population-wide tariffs work well for large-scale manufacturing contracts, they are often unable to predict accurately the numbers of each size needed at training centres because of age biases in the soldiers processed and at smaller unit levels because of age, gender, and race biases that result from sampling error and the secondary effects of rank and occupational requirements inherent in the unit's military mission. Since contemporary combat scenarios involve rapid deployments that rely upon pre-positioned pallets of equipment, unit-specific tariffing plays a critical role in military logistical support. Tariffs must be accurate in order to ensure sufficient numbers of the sizes needed in critical equipment such as chemical protective overgarments, body armour, and boots.

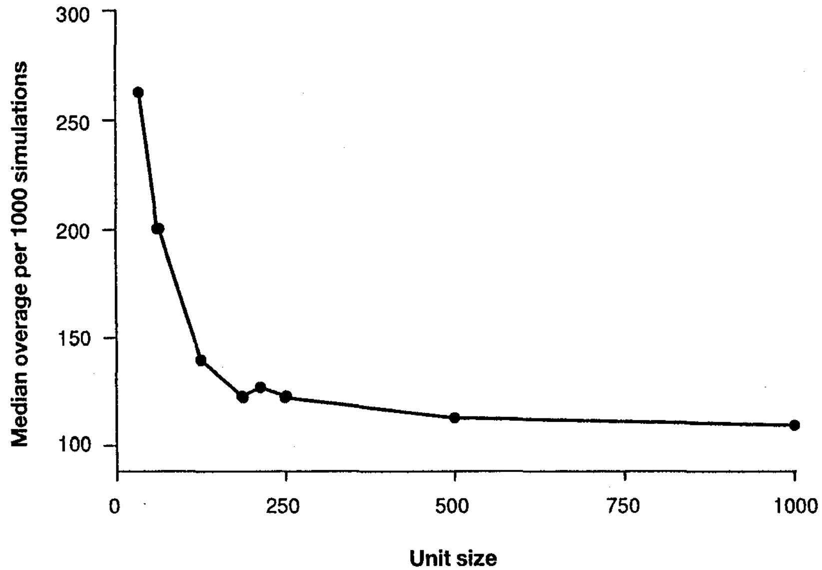

Fig. 12.5. Excess uniforms needed as a function of the number of soldiers to be fitted in a single event.

Ongoing research by the US Army is addressing the statistical limitations of unit-specific tariffing through statistical simulations with its 1988 database in which randomly sampled units of various size and gender composition are issued uniforms based upon prevailing Army sizing systems and tariffs. The size category with the largest relative shortfall is then used to estimate the number of uniforms needed (expressed as a percentage of the number of soldiers in the unit) to ensure that everyone gets an adequately fitted uniform at a single issuing event. Preliminary results for a combat uniform coat are presented in Fig. 12.5. Such functions can be used by Army logisticians in assessing the feasibility and cost of pre-positioning equipment for various organizational levels.

Anthropometry and workstation design

Anthropometry is also critical to the design of crewstations in aircraft, armoured vehicles, and ships, not to mention artillery firing stations, field kitchens and field hospitals. Applied anthropometry in these systems is intended to optimize the man–machine interfaces that are critical to mission performance. Since most major military hardware systems are developed under civilian contract, the methods used in applying anthro-

pometric data to workstation geometry derivation can vary considerably, and many details of design development are proprietary. Nevertheless, a general approach is shared by all human engineers in workstation design, and this involves task identification, dimension selection, geometry derivation, workstation testing and validation, and accommodation mapping (Roebuck *et al.*, 1975; McConville, 1978).

Task identification involves enumeration of critical tasks that must be performed at the workstation, and defining the man–machine interfaces that influence task success and safety. Aircraft pilots, for example, require appropriate visual fields, must be able to actuate all hand and foot controls, must have adequate canopy, instrument panel, and emergency egress clearances, and must be supported in safe and comfortable postures for extended missions and emergency operations (MIL-STD-1333B, 1976). These operational requirements automatically indicate a set of key anthropometric variables that will 'drive' the workstation geometry. Commonly used key workstation dimensions include: seated eye height, functional (arm) reach, seated acromion height, buttock–knee length, and seated knee or popliteal height (Kennedy, 1986; MIL-STD-1333B, 1976; Hendy, 1990; Rothwell & Pigeau, 1990; Zehner *et al.*, 1992). As in CIE applications, a limited set of key dimensions is explicitly accommodated in the design process, and a more extensive set of dimensions critical to system function may be addressed indirectly through various statistical estimation techniques.

Application of key dimensions in the design process is considerably more complex in workstations than in clothing because the whole body must be accommodated within a single design and because the anthropometric 'worst case' models usually do not involve uniformly large or small individuals, but rather individuals with extreme body proportions (for example, a pilot with short trunk and long legs). Derivation of a seated workstation with vision requirements usually starts with seated eye height being used to determine the range of seat adjustability required to position all operators in the target population on the operational sight lines. Then functional reach and acromial height are used to orient and locate instrument panels within the operator's reach throughout the range of seat adjustment. Foot-operated controls and the inferior edge of the instrument panel are located using buttock–knee length and knee or popliteal heights. Once these fundamental aspects of geometry are determined, head, knee, and emergency egress clearances are ensured. The order in which these steps are undertaken varies as a function of task priorities and other design constraints, and may also vary as a function of the actual method used to arrive at design values.

Several approaches are used to derive anthropometric design values for input into workstation models, but most human engineering specialists agree that combinations of worst-case proportions are desirable (Roebuck *et al.*, 1975; Hendy, 1990; Zehner *et al.*, 1992). Early USAF geometries were based upon 'extreme' regression estimates such as the minimum reach expected for the 1st and 99th percentile sitting eye heights (Kennedy, 1986). Most recently, the USAF recommends a principal components approach that reduces the key and critical anthropometric variable space to two or three dimensions, and then identifies extreme body proportions as mid-quadrant points on a 90% accommodation circle or sphere in that space (Robinson *et al.*, 1992; Zehner *et al.*, 1992). The United States Navy (USN) also bases its design requirements upon combinations of extreme body proportions presented as matrices of test cases (Arnoff, 1987).

Validation of military workstation geometries used to rely heavily upon task simulation by clothed subjects in full-scale 'mock-ups'. Today, however, early design concepts can be created within computer-aided design (CAD) environments and tested against three-dimensional man-models such as Combiman, Boeman, Sammie, and Jack (see Rothwell, 1985, 1989; Kroemer *et al.*, 1989; Paquette, 1990 for reviews). In fact, computer programs that simulate cockpit 'checks' on critical tasks can now be run so quickly that iterative testing using whole populations of individuals (real surveys or randomly generated populations) is feasible. These results can be readily incorporated into the design process itself, or used to 'map' the anthropometric accommodation envelope for systems already in the field (Bittner, Morissey & Moroney, 1975; Hendy, Anderson & Drumm, 1984; Rothwell & Pigeau, 1990). Although simulated fit-testing with computerized man-models should never replace full-scale human factors evaluations or individual pilot-cockpit checks because of their limitations in replicating realistic body postures and dimensions of the clothed or equipped operator (Rothwell, 1989), the integration of mathematical man-models and CAD technology is already revolutionizing military workstation design.

Sex and racial heterogeneity in design and sizing

Anthropometry plays a crucial role in quantifying the diversity of body sizes and shapes that attend the gender and racial heterogeneity present in US military populations. Most military systems were designed based upon male data, and initial efforts at gender-integrated protective equipment involved simply scaling down the male patterns into smaller sizes and lengths (Gordon, 1986; Reeps, Pheeny & Brady, 1990). Since the

body proportions of women differ significantly from those of men (Robinette, Churchill & McConville, 1979) the scaled-down clothing and equipment does not fit women well (Woodward *et al.*, 1981; Reeps *et al.*, 1990). Similarly, most (if not all) contemporary military aircraft were designed for men, and their anthropometric accommodation envelopes may exclude large percentages of women (Schopper, 1986; Coblentz, Mollard & Ignazi, 1990; Rothwell & Pigeau, 1990; Turner, 1990).

Military research on gender differences in body size and proportion has explored both the nature and magnitude of male–female differences in general (Robinette *et al.*, 1979) and after controlling for potential key sizing dimensions (McConville *et al.*, 1981; Schafer & Bates, 1988). The results of these studies suggest that gender-integrated sizing programmes may be possible for two-piece field uniforms and some field equipment, but are unlikely to be successful in dress uniforms or in one-piece coveralls.

Gender-integrated sizing involves several unique aspects (Gordon, 1986). The best key dimensions are those that maximize the separation of men and women into separate size categories, thus minimizing the within-size variation due to sexual dimorphism. With optimal key dimensions, there is usually a region of larger sizes worn primarily by men; a region of smaller sizes worn primarily by women; and a central region of gender overlap where sizes will be worn by both men and women (see Figure 12.4, for example). Since computerized pattern grading systems operate with a great deal of interpolation between landmarks, certain aspects of master pattern shape and proportion are carried automatically throughout the sizing system. Thus preparation of a single master pattern in a central, gender-integrated size and subsequent grading of the pattern into male- and female-specific regions of the sizing system compromises fit for individuals in gender-specific areas where pattern proportions are unique. Separate master patterns are therefore drafted for each region: male regression equations are used to specify design values for the upper region; female regression equations are used for the lower region. In the central region, both male and female regression estimates are calculated, and when they are quite different, the more extreme value, regardless of gender, is selected. Computation of separate regression equations and design values for each gender is a critical feature of this approach because pooling the genders will result in equations that describe neither gender well, and if the database reflected the prevailing 89% male composition of the Army, for example, the anthropometric variation attributable to the female minority would have little impact upon parameter estimates. Similar approaches can be taken in workstation design, beginning with the multivariate accommodation specifications that might arise from separate male and female analyses, with selection of the most extreme midquadrant points, regardless of gender (Meindl *et al.*, 1993).

Variation in body size and shape attributable to population differences is equally important in military anthropometry. However, until recently there were insufficient *human engineering* data on military minority groups to assess the extent to which racial variation need be accommodated in military systems and to address anthropometric design solutions. Recent research by the US Army, however, clearly indicates that racial minority groups differ sufficiently in body size alone so as to be differentially disaccommodated by materiel systems designed against Army-wide summary statistics (Walker, 1991). These results suggest that race-specific anthropometric distributions should be considered at both the accommodation requirement and engineering design value stages of materiel system development for those dimensions known to be 'race-sensitive' (see Clauser *et al.*, 1986a,b for a discussion). Race-specific parameter estimates can be incorporated relatively easily into the sizing and workstation procedures outlined above. In fact, Navy women's uniform patterns (Robinette *et al.*, 1990) and Air Force face-forms (Annis, 1985) already incorporate some design values set solely by minority groups with more extreme distributions than the population as a whole. Racial differences in torso vs. limb lengths may be critical to workstation geometries, and these can be addressed by deriving multivariate accommodation criteria separately for different racial groups and then choosing the most extreme of the extreme midquadrant points derived (Meindl *et al.*, 1993).

Secular trends

Because some military systems take decades to field, and many are in use for decades, secular trends in body size are an important issue in military anthropometry. Most research is geared to projecting body size distributions in the 20 to 30 year future, and these projections are sometimes substituted for contemporary values when a new system is developed. The study of secular trends in military populations is tricky because they are not biological populations *per se*, but rather the result of 'immigration' by civilians from many different biological populations, each of which may have its own rate of change. Military secular trends are thus the result of at least three fairly independent factors: (i) secular trends occurring in biological populations; (ii) changes in social attitudes, military recruitment strategies, and accession standards that influence who 'immigrates' into the military; and (iii) changes in physical fitness

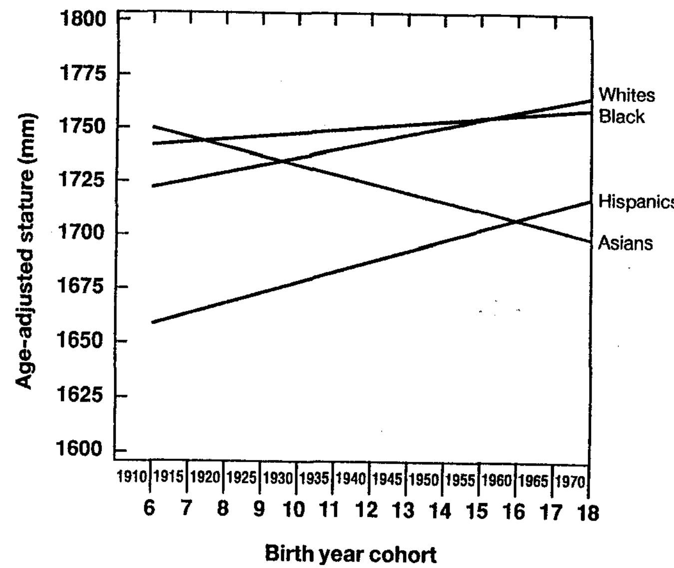

Fig. 12.6. Race-specific secular trends in stature for US Army males. The equations for the lines are as follows. Whites, $y = 1700 + 3.71\,x$, see = 5.11, $r = 0.847$; Blacks, $y = 1732 + 1.46\,x$, see = 5.86, r = 0.480; Hispanics, $y = 1626 + 5.08\,x$, see = 6.72, $r = 0.823$; Asians, $y = 1779 - 4.88\,x$, see = 10.27, $t = -0.623$; for all equations, $p = 0.000$.

requirements that directly influence the anthropometric parameters of members of the military (Greiner & Gordon, 1990, 1991, 1992).

Secular trends in body size are usually estimated from age-corrected data derived from temporally sequential studies on the 'same' population. Until recently, this has also been the approach used in military studies of secular trends, despite the questionable continuity of military populations in a biological sense. The biologically heterogeneous nature of the US military is relatively easily accommodated in secular trend models by estimating trends for individual racial groups (see Fig. 12.6) and weighing these estimates according to demographic projections when predictions are desired (Greiner & Gordon, 1990). However, body size predictions for future military populations are extremely sensitive to differences in age and race composition, and the factors influencing demographic composition are often unpredictable and temporally unstable. Even within-race estimates exhibit temporal perturbations such as the negative secular trend for stature in Asian soldiers. This trend reflects a shift in the origins of Asian soldiers from predominantly American-born Japanese to predominantly foreign-born Filipino (Greiner & Gordon, 1992). The instability of cultural factors influencing the composition of military populations thus makes projections more than 10–20 years into the future tenuous at best, and for some groups, such as Army women, it has made interpretation of even race-specific secular trends extremely difficult (Greiner & Gordon, 1991).

New directions in military anthropometry

New technologies such as helmet-mounted information displays and multilayered, modular, protective clothing demand increasingly more close-fitting materiel systems. In response to these needs, three-dimensional morphometry has become a critical area of ongoing research in military anthropometry. Current work by the USAF on three-dimensional surface digitizing has focused on scans of the head and face to improve the fit of helmets, oxygen masks, and the integration of night vision goggles and helmet-mounted visual displays. The USAF Cyberware scans include 130 000 surface points. Subjects are scanned bare and with helmets and masks in place. Ongoing research by the USAF includes automation of landmark identification, software to facilitate storage and manipulation of the huge databases produced by scanning technologies, and multivariate statistical methods to identify extreme body sizes and shapes in populations of head and face scans. The application of surface and tissue scanning technologies to ergonomic man-model enfleshment, casualty reduction models, and materiel system design and models, and materiel system design and sizing, promises to be a critical area of basic research for all US services in the coming decades.

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