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다변량 정규분포 모의모형을 이용한 물자운반작업을 수행하는 작업자의 인체 치수 및 관절염력의 예측에 관한 연구

Estimation of Anthropometric Body Dimensions and Joint Strengths of a Worker Performing Manual Materials Handling Tasks Using a Multivariate Normal Simulation Model

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Abstract

The primary objective of the research is to develop a mathematical method to incorporate the variability of anthropometric body dimensions and joint strengths of individuals in a biomechanical analysis. A multivariate normal simulation model estimated anthropometric body dimensions and joint strengths of the random link-person, based on the assumptions that the variables of body dimensions and joint strengths are correlated and follow normal distributions. Statistical comparative analysis demonstrated that the random link-person represented a more realistic human-like form in an anthropometric sense than the proportional link-person whose body dimensions were estimated proportionally. Estimated joint strengths for the random link-person, however, did not match the measured joint strengths as closely as the estimated body dimensions. The random link-person will allow biomechanical analysis of manual materials handling tasks to be individualized with respect to the anthropometry and a static strength.

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I. INTRODUCTION

Working with anthropometric data as input to biomechanical models, the practice has arisen of designating small, average, and large individuals as 5^{th} percentile, 50^{th} percentile and 95^{th} percentile, respectively. They are defined as "common percentile individuals" with 5^{th}, 50^{th}, or 95^{th} percentiles in all body dimensions [8]. However, this rather simplified categorization of the population entails a problem when they are thought to represent all people in a population [4]. These percentile individuals are not representative of anyone because great deviation in percentiles is commonplace and natural among an individual's body dimensions and proportions [1, 15]. Therefore, when a group of individuals is selected to meet one critical dimension, other relevant dimensions of those individuals would inevitably fluctuate widely [12]. Moroney et al. [13] demonstrated that the exclusion of 10% (range from 5^{th} through 95^{th} percentiles) of the population on each of 13 anthropometric variables resulted in the exclusion of substantially larger percentage (52.6%) of the population.

The proportional percentile concept is implicitly based on the simplistic assumption of a relatively uniform and significantly high correlation coefficient between all pairs of body dimensions. However, this assumption is incorrect because the correlations vary greatly between all pairs of dimensions and also are known to be relatively low within the population [4, 6, 7, 9, 15]. These low intercorrelations cause the discrepancy between percentile values of body dimensions [13]. Therefore, these intercorrelations should be explicitly considered when a multiple of anthropometric dimensions are required [4].

Another problem in biomechanical analysis exists in the characterization of the subject with regard to voluntary strengths. A voluntary strength of a muscle group for the common percentile person is assumed to be equal to the 50^{th} percentile joint strength of a population, regardless of the anthropometric percentile of the person [3]. However, this simple assumption overlooks the great variability of joint strengths within a population. Furthermore, joint strengths have very low correlations with the anthropometric body dimensions. Thus, joint strengths vary widely between people who have the same percentile of stature and body weight.

Use of the common percentile person as input data may degrade the accuracy of a biomechanical posture prediction. This may cause erroneous biomechanical evaluation for manual materials handling tasks. For example, under a preset location of the load, the predicted body posture of a common percentile person will differ from that of "a hybrid percentile" person involving varied percentiles, even though they have the same percentile of stature and weight. This difference results from the random nature of body segment lengths due to the relatively low interrelationship between anthropometric attributes. Differences in body posture will cause variation of the load moments at the joints in motion. The load moments are also influenced by the variation of body segment weights caused by the relatively low intercorrelation between stature and body weight. These load moments have been compared with the joint strengths to test whether one or more of joint strengths are exceeded. Joint strengths of the common percentile worker are predicted by regression functions, which are the 50^{th} percentile of a population. However, this does not properly represent a worker's joint strengths. Percentiles of joint strengths widely vary between workers, despite the same percentile of anthropometry. A worker's percentile of joint strengths is not also common because the correlations between the joint strengths are not perfect ($\rho<1.0$). Furthermore, these joint strengths are also affected by the randomness of anthropometric attributes because they depend on the included angles at the joints of the predicted body posture [3].

The variations of load moments and joint strengths will affect the biomechanical evaluation of manual materials handling tasks. Therefore, inclusion of the interrelationship between body dimensions and joint strengths is required in any biomechanical model. Incorporation of the variations in anthropometric body dimensions and joint strengths will enhance the reliability of any biomechanical job analysis. This research will develop a mathematical method to incorporate these variations in a biomechanical analysis for manual materials handling tasks.

II. A MULTIVARIATE NORMAL SIMULATION MODEL

In this paper, we focus on the

estimation of body dimensions and joint strengths using a statistically correlated simulation model. This model, like a regression model, consists of variables which are all random. However, the simulation model differs from regression models by completely specifying the joint distribution of the variables. Furthermore, the variables in the simulation model play a symmetrical role with no one variable automatically designated as the dependent variable.

In working with anthropometric data, some values can be measured directly or estimated indirectly using a mathematical estimation technique [4]. Measured data are obviously more desirable, but are often either unavailable or unattainable for a subject population. In such cases, the estimation of body dimensions from a statistical simulation model becomes the sole source of design information where only means, standard deviations, and correlation coefficients of body dimensions are available. Any statistical simulation model will never fit real data perfectly, but most body dimensions can be reasonably well represented by a normal distribution within usual design tolerances such as 5%-95% [15].

A simulation model for the distribution of a body dimension can be extended to a "bivariate" simulation model. This model has a joint distribution for correlated body dimension and joint strength. This bivariate simulation technique permits us to estimate, with known levels of confidence, the distributions of values for a body dimension and a joint strength simultaneously. The bivariate simulation model can be extended to a multivariate simulation model, which can include any number of variables representing body dimensions and joint strengths. This simulation model depends in each case on the means and standard deviations of the variables involved, plus all their correlation coefficients. The multivariate simulation model becomes more complex as the number of body dimensions and joint strengths increase to represent an individual performing a manual materials handling task. However, the multivariate simulation model can reliably estimate the values of a large number of body dimensions and joint strengths with today's digital computer.

In engineering anthropometry, the measurements of most anthropometric body dimensions have been broadly accepted as following a normal distribution. However, frequency distributions of joint strength data have been known to be skewed at the larger values instead of the normally distributed shape [15]. Keyserling [10] has suggested that a lognormal distribution can sometimes fit joint strength better than a normal distribution. However, Stobbe [16] has recommended a normal distribution, because lognormal distribution shows only marginal improvement in fitting strength data and may cause practical loss of data interpretation. In this research, a normal distribution is assumed to be an appropriate distribution to characterize all strength variables.

A multivariate normal simulation model was used to create a "random link-person" who had hybrid percentile body dimensions and joint strengths. Since the random link-person includes the intercorrelations between body dimensions, between joint strengths, and between body dimensions and joint strengths simultaneously, the random link-person is more realistic and represents a human-like form which could function like, in fact, an individual person of subject population. In this research, the random link-person is assumed to have nine body dimensions: stature, body weight, foot length, ankle height, kneecap height, upper leg length, torso length, upper arm length, and elbow-to-grip length. This person also has eleven joint strengths: elbow flexion, elbow extension, shoulder flexion, shoulder extension, torso flexion, torso extension, hip flexion, hip extension, knee flexion, knee extension and ankle extension. These represent an operator standing and performing a manual materials handling task in the sagittal plane.

The following multivariate normal simulation algorithm was developed based on Law and Kelton [11] to simultaneously predict intercorrelated anthropometric body dimensions and joint strength:

Algorithm

Let $\mathbf{X}_1, ..., \mathbf{X}_n$ be random variables representing anthropometric body dimensions and $\mathbf{X}_{n+1}, ..., \mathbf{X}_p$ represent joint strengths of a random link-person. If random vector, $\mathbf{X} = (\mathbf{X}_1, ..., \mathbf{X}_n, \mathbf{X}_{n+1}, ..., \mathbf{X}_p)^T$ follows a multivariate normal distribution, $\mathbf{N_n}(\mathbf{m}, \Sigma)$, then $\mathbf{m} = \{E(\mathbf{X}_1), ..., E(\mathbf{X}_n), E(\mathbf{X}_{n+1}), ..., E(\mathbf{X}_p)\} = \{m_1, ..., m_n, m_{n+1}, ..., m_p\}$ is the mean vector and Σ is a covariance matrix with components, Cov $(\mathbf{X}_i, \mathbf{X}_j) = \sigma_{ij} = \sigma_{ji}$, for i, j = 1, 2, ..., p.

Step 1.
Find the mean vector, **m**, from survey data of a subject population.

Step 2.
Find Σ, the covariance matrix computed from standard deviations and correlation coefficients of body dimensions and joint strengths for a subject population.

Step 3.
Determine C_{ij}, an element of **C** from $\Sigma = \mathbf{C}\,\mathbf{C}^T$ using Cholesky's factorization method [14], where **C** is a lower triangular matrix. Matrix **C** is unique because matrix Σ is positive definite and symmetric.

Step 4.
Generate random variables, $\mathbf{U}_1, ..., \mathbf{U}_n, \mathbf{U}_{n+1}, ..., \mathbf{U}_p$ which follow a uniform distribution $\mathbf{U}(0,1)$ respectively.

Step 5.
Generate random variables $\mathbf{Z}_1, ..., \mathbf{Z}_n, \mathbf{Z}_{n+1}, ..., \mathbf{Z}_p$ as identically distributed independent $\mathbf{N}(0,1)$ by transforming the uniformly distributed random variables, $\mathbf{U}_1, ..., \mathbf{U}_n, \mathbf{U}_{n+1}, ..., \mathbf{U}_p$, based on the Polar method.

Step 6.
Generate $\mathbf{X}_i$ as a component of a multivariate normal vector, **X**, such as,

$$\mathbf{X}_i = m_i + \sum_{j=1}^{i} C_{ij}\,\mathbf{Z}_j, \quad \text{for } i = 1, 2, ..., p.$$

Step 7.
Repeat steps 4 to 6 until the required number of random link-people are generated.

2-1. Estimations of Body Dimensions and Joint Strengths

The algorithm of the multivariate normal simulation model was implemented with the Fortran 77 structured program language to estimate the distribution of the values of the 9 body dimensions and the 11 joint strengths for the subject population. This population consists of the United States Air Force personnel. The multivariate normal simulation model used correlation coefficient matrices (Tables 2-1 and 2-3), means, and standard deviations (Tables 2-2 and 2-4) of the body dimensions and the joint strengths as the input data. The body dimensions were estimated from the survey data for the subject population [15]. The joint strengths for the subject population are quoted from the study of Stobbe [16]. The correlations between the stature, weight and the joint strengths were estimated from the relations between stature and standardized strengths (ρ=0.372), and between weight and standardized strengths (ρ=0.43), respectively. Correlations between body segment lengths and joint strengths are here assumed to be the same as those between stature and joint strengths.

Table 2-1. Correlation coefficient matrix of the body dimensions (based on Roebuck et al., 1975)

STAT	1.000								
WEGT	0.493	1.000							
KNHT	0.826	0.440	1.000						
UPLG	0.820	0.601	0.774	1.000					
TOSO	0.633	0.429	0.389	0.417	1.000				
UPAM	0.736	0.382	0.680	0.682	0.438	1.000			
ELRP	0.793	0.427	0.760	0.695	0.446	0.736	1.000		
ANHT	0.395	0.273	0.405	0.343	0.214	0.318	0.378	1.000	
FOOT	0.696	0.440	0.642	0.597	0.419	0.562	0.725	0.275	1.000
	STAT	WEGT	KNHT	UPLG	TOSO	UPAM	ELRP	ANHT	FOOT

abbreviations:

STAT : Stature
WEGT : Weight
KNHT : Kneecap height
UPLG : Upper leg length
TOSO : Torso length
UPAM : Upper arm length
ELRP : Elbow-to-grip length
ANHT : Ankle height
FOOT : Foot length

Table 2-2. Mean and standard deviation of body dimensions for the population of United States Air Force personnel (units: cm for length and kg for weight) (based on Webbs Associates, 1978)

Body dimension	Mean	Standard deviation
Stature	177.34	6.19
Weight	78.74	9.72
Foot length	27.03	1.19
Ankle height	7.04	0.54
Kneecap height	49.65	2.49
Upper leg length	44.31	2.66
Torso length	51.25	3.19
Upper arm length	35.95	1.71
Elbow-to-grip length	35.20	1.62

Table 2-3. Correlation coefficient matrix of joint strengths (based on Stobbe, 1982)

EF	1.000										
EE	0.840	1.000									
SF	0.908	0.867	1.000								
SE	0.881	0.791	0.833	1.000							
TF	0.771	0.725	0.738	0.693	1.000						
TE	0.836	0.774	0.846	0.800	0.740	1.000					
HF	0.725	0.629	0.735	0.791	0.636	0.684	1.000				
HE	0.824	0.680	0.803	0.858	0.688	0.855	0.803	1.000			
KF	0.825	0.793	0.831	0.774	0.716	0.830	0.761	0.817	1.000		
KE	0.762	0.679	0.756	0.820	0.672	0.803	0.772	0.851	0.798	1.000	
AE	0.803	0.719	0.789	0.827	0.630	0.829	0.761	0.819	0.814	0.813	1.000
	EF	EE	SF	SE	TF	TE	HF	HE	KF	KE	AE

abbreviations:
EF : Elbow flexion strength
EE : Elbow extension strength
SF : Shoulder flexion strength
SE : Shoulder extension strength
TF : Torso flexion strength
TE : Torso extension strength
HF : Hip flexion strength
HE : Hip extension strength
KF : Knee flexion strength
KE : Knee extension strength
AE : Ankle extension strength

Table 2-4. Mean, standard deviation, and coefficient of variation of joint strengths (based on Stobbe, 1982)

Joint strength	Mean (Nm)	Standard deviation	Coefficient of variation
Elbow flexion	77.1	19.1	0.248
Elbow extension	47.2	9.5	0.201
Shoulder flexion	70.3	17.3	0.246
Shoulder extension	69.6	21.8	0.313
Torso flexion	142.7	41.9	0.294
Torso extension	328.1	103.4	0.315
Hip flexion	204.6	55.8	0.273
Hip extension	217.8	87.5	0.402
Knee flexion	109.4	32.1	0.293
Knee extension	170.3	59.7	0.351
Ankle extension	138.7	45.9	0.331

2-2. Analysis Of Estimated Body Dimensions

One thousand random link-people with 9 body dimensions and 11 joint strengths were generated using the multivariate normal simulation model. The simulation model directly estimated the values of the body dimensions and the joint strengths for a random link-person with the exception of the lower leg length, because its mean and standard deviation were not available. For this reason, the lower leg length is estimated indirectly as equal to a kneecap height minus an ankle height.

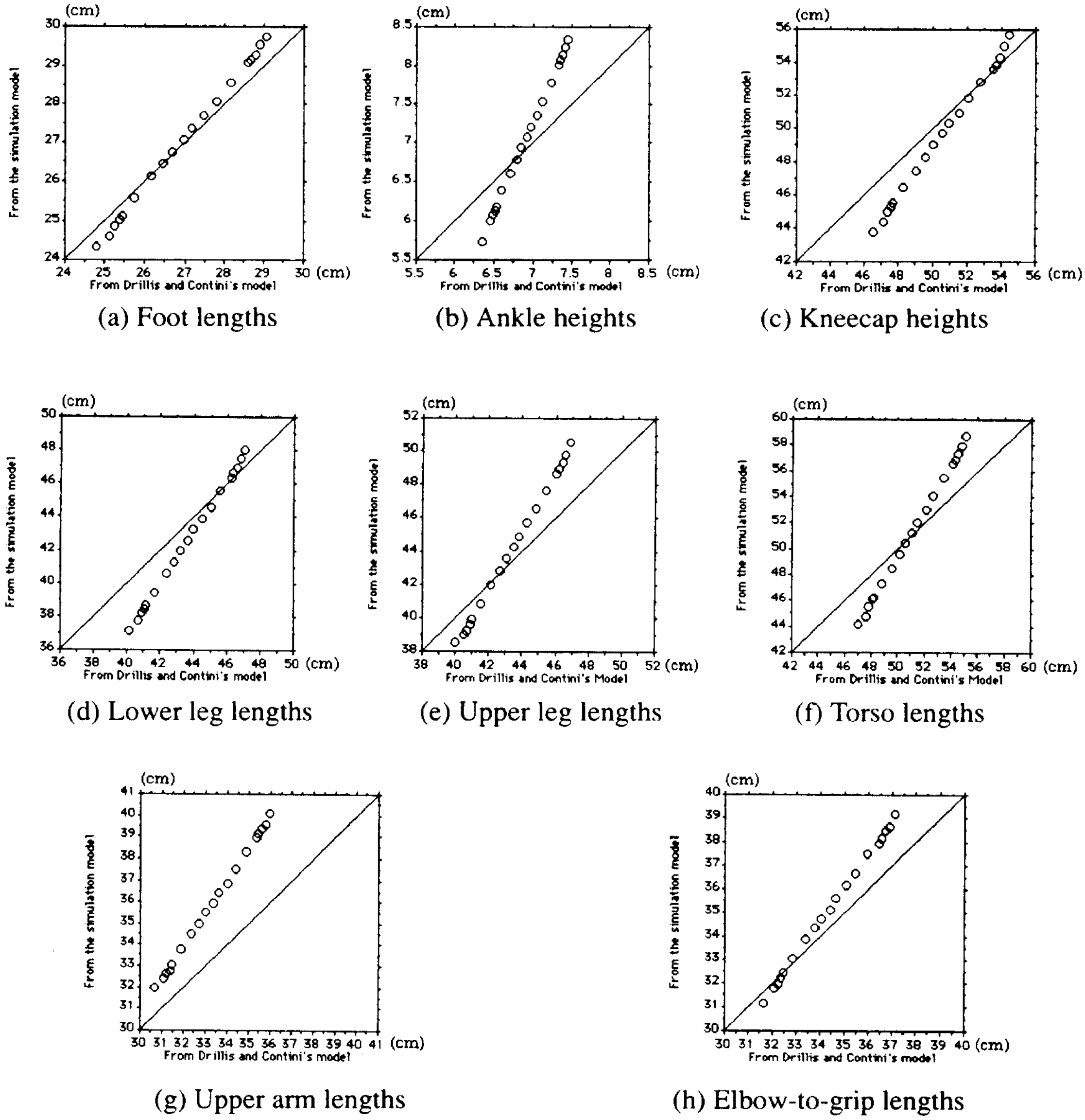
An alternate way to predict body segment length is to use Drillis and Contini's proportionality model which provides an average set of ratios of segment length to stature [3, 5, 15]. These ratios are used to generate "proportional link-people" whose body segment lengths are predicted proportionally from stature. The proportional link-person is characterized as an artificial person based on the simplistic assumption that the body dimensions are simply related in a proportional and straight line manner from the smallest to largest individuals.

Using Drillis and Contini's model, one thousand "proportional link-people" were generated by simply multiplying the ratios of body segment length to body height (Table 2-5) to the randomly generated stature data. The proportional link-person, based on the concept of a constant percentile person, consists of the same body segments as the random link man.

Table 2-5. Proportion of body dimensions for the proportional link-people (unit: % stature) (based on Drillis and Contini, 1966)

Body dimension	Proportion
Foot length	15.2
Ankle height	3.9
Kneecap height	28.5
Lower leg length	24.6
Upper leg length	24.5
Torso length	28.8
Upper arm length	18.8
Elbow-to-grip length	19.4

The percentile comparative analysis of the body dimensions was performed to evaluate which link-person is more human-like in an anthropometric sense. The percentile distributions of the body dimensions for the population of the random link-people were shown to be almost identical with those of the USAF personnel (Table 2-6). Percentile comparison of lower leg lengths and torso lengths between the populations of USAF personnel and the random link-people were not performed because percentile distributions of the body dimensions for the USAF population were not available. However, the ranges of the percentile distributions of the body dimensions for the proportional link-people were smaller than those for the random link-people and for the USAF personnel (Figure 2-1). For ankle height and torso length, the proportionality model overestimated or underestimated the body dimensions in both tails of the percentile distribution when compared with the random link-people (Figures 2-1(b) and 2-1(f)). The percentile values of upper arm length for the random link-people were larger than those for the proportional link-people throughout the whole percentile distribution (Figure 2-1(g)). The deviation between the percentile distributions of the two link-people groups increased as the percentile became greater. For upper leg length and elbow-to-grip length, both models showed quite similar percentile distributions for the range from first percentile to 50th percentile. However, over the 50th percentile, they showed larger deviation as the percentile becomes greater (Figures 2-1(e) and 2-1(h)). On the other hand, kneecap height and lower leg length showed larger deviation of percentile values between the link-people groups for smaller percentiles (Figures 2-1(c) and 2-1(d)).



(a) Foot lengths (b) Ankle heights (c) Kneecap heights

(d) Lower leg lengths (e) Upper leg lengths (f) Torso lengths

(g) Upper arm lengths (h) Elbow-to-grip lengths

Figure 2-1. Percentile comparison graphs for the body dimensions estimated by Drillis and Contini's model and a multivariate normal simulation model

Table 2-6. Percentile comparison of distributions of the body dimensions for the populations of the USAF personnel and the random link-people (unit: cm)

(a) Stature

Population	1%	5%	10%	50%	90%	95%	99%
USAF	163.2	167.2	169.4	177.3	185.4	187.7	191.8
Random link-person	163.2	167.3	169.3	177.4	185.3	188.0	191.2

(b) Body weight (unit: kg)

Population	1%	5%	10%	50%	90%	95%	99%
USAF	57.9	63.6	66.6	78.2	91.5	95.6	103.3
Random link-person	56.9	63.9	67.3	79.0	92.0	95.0	101.9

(c) Foot length (unit: cm)

Population	1%	5%	10%	50%	90%	95%	99%
USAF	24.3	25.1	25.5	27.0	28.6	29.0	29.9
Random link-person	24.3	25.1	25.6	27.1	28.6	29.1	29.7

(d) Ankle height (unit: cm)

Population	1%	5%	10%	50%	90%	95%	99%
USAF	5.8	6.2	6.4	7.0	7.7	8.0	8.4
Random link-person	5.7	6.2	6.4	7.1	7.8	8.0	8.4

(e) Kneecap height (unit: cm)

Population	1%	5%	10%	50%	90%	95%	99%
USAF	44.0	45.7	46.5	49.6	52.9	53.9	55.7
Random link-person	43.8	45.5	46.4	49.7	52.9	53.7	55.8

(f) Upper arm length (unit: cm)

Population	1%	5%	10%	50%	90%	95%	99%
USAF	32.1	33.2	33.8	35.9	38.2	38.8	40.0
Random link-person	32.0	33.1	33.8	35.9	38.3	38.9	40.1

(g) Elbow-to-grip length (unit: cm)

Population	1%	5%	10%	50%	90%	95%	99%
USAF	31.7	32.6	33.1	35.2	37.3	37.9	39.1
Random link-person	31.2	32.5	33.1	35.2	37.5	37.9	39.2

Mean values, standard deviations, and ranges of the distributions of the body dimensions were estimated for the population of the random link-people (Table 2-7). The mean, standard deviation, and range of each body segment length distribution were shown to be almost identical to those of the measured data for the USAF personnel (Tables 2-2 and 2-7). However, the estimated mean value (33.3 cm) of the upper arm length distributions for the proportional link-people showed a statistically significant difference (α=0.05) from that (36.0 cm) of the random link-people. The estimation of body segment lengths with the proportionality model showed that the standard deviations and the ranges of the estimated body segment length distributions were consistently smaller than those for the random link-people and the USAF population. That is, the proportionality model always underestimates the variability of the distributions of the body dimensions (average underestimation=64%).

Table 2-7. Mean, standard deviation and range of distributions of the body dimensions for the population of the random link-people (unit: cm for length and kg for weight)

Body dimension	Mean	Standard deviation	Minimum	Maximum
Stature	177.4	6.25	156.6	195.7
Weight	79.4	9.59	48.1	109.4
Foot length	27.1	1.17	23.6	30.9
Ankle height	7.07	0.55	5.4	8.9
Kneecap height	49.7	2.54	40.8	58.8
Lower leg length	42.6	2.37	34.3	50.5
Upper leg length	44.3	2.65	35.4	52.7
Torso length	51.3	3.17	40.0	60.2
Upper arm length	36.0	1.76	30.4	41.9
Elbow-to-grip length	35.2	1.69	29.9	39.9

The distribution of body proportion was investigated within the population of random link-people. For an individual random link-person, the body proportion of each segment was defined as the ratio of body segment length to stature. One thousand body proportions were found for each body segment. The distributions of the body proportions are shown in Table 2-8. A few body proportions have a relatively wide range of dispersion which may cause a wide deviation of estimated body segment lengths within the population of the random link-people. For example, torso proportion varies from 24.1% to 32.7% of stature throughout the population of the random link-people; a considerable variation. This means that among men of average stature, torso length may vary as much as 15.3 cm. Furthermore, this torso proportion of the random link-people has virtually no correlation with stature (ρ torso & stature=0.125). The other body proportions also showed very low inter-correlationship with stature.

Table 2-8. Mean, standard deviation, minimum and maximum of the body proportions to stature for the population of random link-people (unit: % stature)

Body dimension	Mean	S. D.	Minimum	Maximum
Foot length	15.3	0.47	13.5	16.6
Ankle height	4.0	0.29	3.1	5.0
Knee height	28.0	0.82	25.3	30.6
Lower leg length	24.0	0.84	21.5	26.5
Upper leg length	24.9	0.92	22.3	27.6
Torso length	28.9	1.35	24.1	32.7
Upper arm length	20.3	0.65	18.5	22.5
Elbow-to-grip length	19.9	0.57	18.1	21.9

2-3. Analysis of Estimated Joint Strengths

As mentioned above, the multivariate normal simulation model estimated the distribution of values of 11 joint strengths and 9 body dimensions for one thousand random link-people. The predicted values of 11 joint strengths were sorted in ascending order based on stature. The estimated values of each joint strength were stratified by the stature range which was sorted in ascending order. The stratified distributions of joint strengths demonstrated a similar pattern, such that the mean value of the estimated strength data has a tendency to be larger as stature is taller. However, they consistently have a very wide range of dispersion through the whole population. This distribution characteristic confirms that stature is not well correlated with joint strength.

A percentile comparative analysis was performed between the estimated values and the measured data of joint strengths. It showed the followings:

-- The percentile distributions of elbow flexion, elbow extension, torso flexion, and knee flexion strengths for the population of random link-people were almost identical with those of the measured joint strengths (Tables 2-9(a), 2-9(b), 2-9(e), and 2-9(i)).

-- The 5^{th} and 50^{th} percentile values of the estimated and the measured data of shoulder flexion strength match very well, but the simulation model slightly underestimated the 95^{th} percentile value when compared with that of the measured joint strength data (Table 2-9(c)).

-- For torso extension strength, the simulation model overestimated the 5^{th} and 50^{th} percentile values, but slightly underestimated the 95^{th} percentile value, when compared with the percentile distribution of the measured joint strength (Table 2-9(f)).

-- The shoulder extension, hip flexion, hip extension, and knee extension strengths for the population of random link-people has a similar percentile distribution pattern, such that the 5^{th} and 95^{th} percentile values were underestimated, but the 50^{th} percentile value was overestimated, when compared with the percentile values of the measured joint strengths (Tables 2-9(d), 2-9(g), 2-9(h), and 2-9(j)).

-- Percentile distribution of estimated values for the ankle extension strength tended to underestimate the 5^{th} and 95^{th} percentile values, but have almost the same value at the 50^{th} percentile, when compared with that of the measured data (Table 2-9(k)).

The deviation of percentile values, between the estimated and the measured joint strength data, may be caused by the relationship between sample size and variability of joint strengths. A sample size, required to represent a subject population with a predetermined level of accuracy, is approximately proportional to the size of estimated variance [15]. Therefore, the bigger the variance of a subject population, the larger the sample

Table 2-9. Percentile comparison between distributions of the measured and the estimated joint strengths (unit: Nm)

(a) Elbow flexion strengths

Elbow Flexion	5%	50%	95%
Measured value	43.8	77.7	114.2
Estimated value	44.3	78.0	111.3

(b) Elbow extension strengths (unit: Nm)

Elbow Extension	5%	50%	95%
Measured value	30.0	46.3	65.0
Estimated value	31.7	47.9	63.7

(c) Shoulder flexion strengths (unit: Nm)

Shoulder Flexion	5%	50%	95%
Measured value	41.8	70.6	108.8
Estimated value	42.8	71.2	99.3

(d) Shoulder extension strengths (unit: Nm)

Shoulder Extension	5%	50%	95%
Measured value	39.6	66.7	118.9
Estimated value	32.6	71.4	107.0

(e) Torso flexion strengths (unit: Nm)

Torso Flexion	5%	50%	95%
Measured value	79.3	143.0	215.4
Estimated value	76.3	144.7	214.9

(f) Torso extension strengths (unit: Nm)

Torso Extension	5%	50%	95%
Measured value	146.8	323.9.	507.4
Estimated value	162.2	333.3	501.9

(g) Hip flexion strengths (unit: Nm)

Hip Flexion	5%	50%	95%
Measured value	126.5	196.7	316.7
Estimated value	111.0	208.4	296.8

(h) Hip extension strengths (unit: Nm)

Hip Extension	5%	50%	95%
Measured value	100.3	203.7	422.7
Estimated value	79.8	222.1	373.1

(i) Knee flexion strengths (unit: Nm)

Knee Flexion	5%	50%	95%
Measured value	58.4	112.6	161.8
Estimated value	56.3	110.6	163.1

(j) Knee extension strengths (unit: Nm)

Knee Extension	5%	50%	95%
Measured value	89.8	148.0	293.6
Estimated value	76.7	173.0	275.6

(k) Ankle extension strengths (unit: Nm)

Ankle Extension	5%	50%	95%
Measured value	73.3	136.6	244.2
Estimated value	65.8	138.7	216.2

size must be. In this research, the percentile values of the measured joint strengths were computed from the sample of 35 male subjects [16]. However, this sample size may not be large enough to guarantee accurate estimation of percentile distribution of some joint strengths because they have considerable variability. Coefficient of variation, the simple restatement of standard deviation as a percent of mean, revealed that the joint strengths with smaller coefficients of variation tend to show smaller deviation from the percentile comparison. For example, elbow flexion, elbow extension, shoulder flexion, torso flexion, and knee flexion strengths, whose estimated percentile distributions are almost identical with those of the measured data, have coefficients of variation of 0.248, 0.201, 0.246, 0.294, and 0.293, respectively. On the other hand, torso extension, hip extension, knee extension and ankle extension strengths with a moderate deviation of percentile values showed higher level of coefficient of variation, 0.315, 0.402, 0.351, and 0.331, respectively. Therefore, a large variability of some joint strengths within such a small sample size may result in the deviation of percentile values between the measured and the estimated percentile values of joint strengths.

Strength data frequency distributions are typically skewed to the large values instead of being normally distributed as are many dimensional distributions [15, 16]. However, in this research, we assumed that a joint strength follows a normal distribution for practical convenience. Thus, the estimation of various joint strength percentiles from the means and standard deviations using normal probability statistics are likely to cause error when compared with the measured percentiles.

III. CONCLUSIONS

The populations of the random link-people and the proportional link-people were compared to investigate their compatibility with the population of the USAF personnel in terms of anthropometry and joint strengths. The conclusions from the comparison are discussed below:

1. The random link-person was more human-like than the proportional link-person in an anthropometric sense. This conclusion is based on the statistical comparative analysis

which demonstrated that the random link-person was closer to the actual anthropometric measurement for the population of USAF personnel than the proportional link-person. A percentile comparison showed that the percentile distribution of body dimensions for the population of random link-people was almost identical to those for the population of USAF personnel. Mean, standard deviation and range of distributions of the body dimensions for the random link-people were almost same as those for the USAF personnel. By contrast, the population of the proportional link-people showed considerable deviation of percentile values when compared with the percentile distributions for the population of USAF personnel. Furthermore, the proportional link-people underestimated the variability of the distributions of the body dimensions.

2. Analysis of the random link-people revealed that body proportions varied significantly between individuals within the population. By contrast, the proportional link-person assumed that a body proportion was uniform from the smallest person to the tallest one. For example, torso proportion, defined as the ratio of the torso length to stature, showed the largest dispersion (24.1% to 32.7%) throughout the population of random link-people. Furthermore, a correlation analysis showed that the torso proportions for the random link-people have virtually no interrelation with stature distribution. Thus, there is inherent variability in torso proportion of random link-people which is not related with stature. Because of the inherent variability, torso length can vary widely for any stature. For example, among people of average stature, torso length can vary as much as 15.3 cm. This holds true for the other body proportions.

3. The mean value of the upper arm length for the random link-people was almost identical to that for USAF personnel. By contrast, a statistical significance test showed that the mean value of the upper arm length for the proportional link-people was significantly ($\alpha = 0.05$) smaller than that of the random link-people .

4. Estimated joint strengths for the random link-people did not match the measured joint strengths as closely as body dimension. A percentile comparative analysis showed that considerable deviations of percentile values were found between several estimated and measured joint strengths. These percentile deviations may be caused by a relationship between sample size and sample variance. From the percentile comparison analysis, the estimated joint strengths had considerable deviation in percentile distributions, when compared with those of corresponding measured joint strengths with higher variances. However, estimated joint strengths showed almost identical percentile distributions with those of the corresponding measured joint strengths, when the measured joint strengths have lower variances. Another possible reason for the deviation of percentile distribution is the assumption of normality for distribution of the joint strength in this research. A joint strength has been known to follow a lognormal distribution rather than a normal distribution. However, in this research, a normal distribution was assumed for a joint strength for the convenience of data interpretation.

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