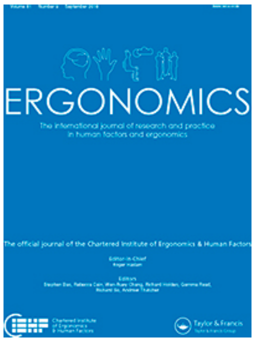

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Modelling of maximum acceptable load of lifting by physical factors

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Matching the job demands to a person's physical characteristics is an effective method of reducing the risk involved in a manual materials-handling task. Seventy-three male and 73 female industrial workers served as subjects. Maximum Acceptable Load of Lifting (MAL) was determined psychophysically under each combination of the following task conditions: six ranges of lift (floor to knuckle, floor to shoulder, floor to reach, knuckle to shoulder, knuckle to reach and shoulder to reach); four lifting frequencies (2, 4, 6 and 8 l/min); and three box sizes (30·48, 45·72 and 60·96 cm). A factor-score-based model ($R^2 = 0{\cdot}924$) is developed in this paper based on 100 subjects for predicting an individual's MAL and for describing his/her physical characteristics in terms of strength and anthropometric scores. The model was validated on the remaining 46 subjects and was shown to be superior to the previously developed models from the same data set.

1. Introduction

It is generally accepted (NIOSH 1981) that the manual materials-handling (MMH) task is a primary source of most of the musculoskeletal injuries in industry. Lahey (1984) reports Canadian statistics and notes that, following the common cold, back pain is the second leading cause of absenteeism in industry. In the United States, 400 000 workers suffer disabling back injuries every year (*Accident Facts* 1978), with the resulting direct cost to industry estimated to be $20 billion annually. In addition, the suffering of the injured and their families extends beyond the level of financial compensation.

To minimize the injuries caused by MMH activities as well as to maximize job productivity, job demands should match the capacities of individuals. Job demands for MMH activities are usually described in terms of type, frequency, range/distance of handling, with weight, container characteristics and location of the load. Individual capacities, in terms of anthropometric measurements and/or physical capacity (such as maximum aerobic capacity), are commonly examined in the literature. Examples of the use of such a rationale in job design are in the Job Severity Index (JSI) technique (Ayoub *et al.* 1986, Liles 1986).

The objective of this study was to develop a model to predict a person's MAL for given task conditions (frequency and range of lift), and to describe the individual's physical characteristics in terms of strength and anthropometric scores.

2. Rationale

Various mathematical models have been developed for predicting the MAL that a person can handle safely and have incorporated numerous worker and task variables. For example, in some models a single predictor variable was used (Poulsen and Jorgensen 1971, McConville and Hertzberg 1966); while others contained more than 10 (Ayoub *et al.* 1980).

One such model for MAL (Poulsen and Jorgensen 1971, Ayoub *et al.* 1980, Mital and Ayoub 1980, Aghazadeh and Ayoub 1985) uses a psychophysical methodology and a set of strength tests as predictors, the selection of which was largely dependent on the statistical technique of stepwise regression.

However, the selection of one strength test rather than another makes the interpretation of models difficult. For instance, a set of strength test data could be collected as follows: arm strength, leg strength, shoulder strength, back strength, and composite strength (tested as a lifting strength in a squatting position at 38-cm height from the floor). Analysis of several available data sets (Ayoub *et al.* 1978, Plott 1983, Jiang 1984), shows that these five strength variables are highly correlated (see table 1). It is also believed that while all five variables are correlated with lifting capacity, each individual strength (e.g., shoulder strength) might contribute differently under different lifting situations (Ayoub *et al.* 1980). For example, arm strength may contribute more than leg strength in determining a lifting capacity from knuckle to shoulder height. The selection of any subset of these five strength tests must result in lost information from the tests other than the subset selected. Therefore, a 'strength score' could be used to represent all strength data. The strength factor can be obtained by using factor analysis to factorize all strength tests into one underlying structure based on their correlations, and then calculating the strength score as a function of all strength variables. The

Table 1. Correlation coefficients (Pearson) among five static-strength variables.

Source*		Arm	Back	Leg	Shoulder	Composite
Arm	(1)	—	0·69	0·78	0·86	N/A
	(2)	—	0·67	0·80	0·79	0·75
	(3)	—	0·86	0·81	0·79	0·89
Back	(1)	0·69	—	0·73	0·79	N/A
	(2)	0·67	—	0·76	0·72	0·83
	(3)	0·86	—	0·85	0·86	0·91
Leg	(1)	0·78	0·73	—	0·79	N/A
	(2)	0·80	0·76	—	0·80	0·85
	(3)	0·81	0·85	—	0·74	0·90
Shoulder	(1)	0·86	0·79	0·79	—	N/A
	(2)	0·79	0·72	0·80	—	0·82
	(3)	0·79	0·86	0·74	—	0·77
Composite	(1)	N/A	N/A	N/A	N/A	—
	(2)	0·75	0·83	0·85	0·82	—
	(3)	0·89	0·91	0·90	0·77	—

*(1) Plott (1983) (15 subjects).
(2) Data from Ayoub *et al.* (1978) (146 subjects).
(3) Data from Jiang (1984) (12 subjects).

purposes of doing this are to include more representative variables and to reduce the dimensions in a prediction model.

Factor scores are more appealing than numerous data-level variables because of their parsimony and explainability. Cattell (1966a) and Guertin and Bailey (1970) suggest using factor scores rather than unfactored data-level variables as predictors in multiple regressions. Morris (1980) has summarized his work since 1975 (1975a–c, Morris and Guertin 1977), and notes that using factor scores as predictors is superior because of parsimony, meaningfulness, and lack of correlation among predictors.

3. Method

The experimental data for this study was adopted from Ayoub *et al.* (1978), in which experimental details have been described. For convenience, the experimental procedure is summarized here.

Seventy-three male and 73 female workers recruited from local industries served as subjects in the experiment. All subjects had a minimum of six months MMH experience immediately preceding participation in the experiment. A balanced, incomplete block factorial design was used. Six ranges of lift—floor to knuckle (FK), floor to shoulder (FS), floor to overhead reach (FR), knuckle to shoulder (KS), knuckle to reach (KR), and shoulder to reach (SR)—and four lifting frequencies—2, 4, 6 and 8 lifts/min—were selected for the study. The boxes had three dimensions in the sagittal plane—30·48, 45·72 and 60·96 cm. Since lifting capacity for each task condition was determined psychophysically (Ayoub *et al.* 1978, Snook 1978), each individual was given approximately 20 minutes to determine the maximum weight he or she was willing to lift without becoming exhausted or overheated for an 8-hour working period.

Anthropometric and strength/stamina measurements (Ayoub *et al.* 1978, Mital and Ayoub 1980) were made in order to construct an individual's physical characteristics data base. Each measurement was selected on the basis of its supposed correlation with MAL. The anthropometric measurements were weight, stature, acromial height, knuckle height, standing iliac crest height, knee height, forearm grip distance, chest depth, chest width, and abdominal depth. The strength/stamina tests included shoulder strength, arm strength, composite strength, standing back strength, leg strength, static arm endurance, and dynamic arm endurance. The descriptive statistics for anthropometric, strength, and MAL data are shown in table 2.

Factor analysis was used to form the underlying structure for a set of strength/stamina test data and/or anthropometric data. The essential purpose of factor analysis is to describe, if possible, the covariant relationships among many variables in terms of a number of underlying but unobservable, random quantities or 'factors'. The factor model is derived from correlated variables that can be grouped by their correlations, that is, all variables within a particular group are highly correlated but have relatively low correlations with variables in a different group. Thus each group of variables represents a single underlying construct, or factor, that is responsible for the observed correlation (Johnson and Wichern 1982, p. 401). For example, correlations from the group of strength test scores in arm, shoulder, elbow, back and leg could suggest an underlying 'strength' factor.

Principal factor analysis (Johnson and Wichern 1982, SAS User's Guide 1982) was used to extract factors from all subjects' physical capacity data bases. The extraction operation was based on the correlation matrix of these variables. Related mathematical operations and procedures can be found in Johnson and Wichern (1982) and the SAS User's Guide (1982). Following factor extraction, the oblique procrustes factors

Table 2. Anthropometric measurements, strength testing and lifting capacity data (146 subjects).

Variables	Mean	S.D.	Max.	Min.
Age (years)	33·85	10·33	64·00	18·00
Weight (kg)	71·45	15·25	125·91	48·41
Height (cm)	167·74	8·99	193·10	146·00
Shoulder ht. (cm)	137·66	7·39	161·00	119·60
Knuckle ht. (cm)	73·62	4·42	88·00	63·30
Abd. dep. (cm)	21·08	4·26	35·40	12·90
Chest dep. (cm)	20·34	2·65	29·40	14·50
Grip distance (cm)	32·63	2·51	39·90	24·10
Shoulder strength (kg)	39·15	15·25	74·85	13·79
Arm strength (kg)	30·47	10·64	68·48	11·82
Composite strength (kg)	89·10	33·49	181·36	36·06
Back strength (kg)	60·56	18·48	114·85	26·06
Leg strength (kg)	105·80	34·01	186·97	38·18
Static endurance (min)	3·86	2·07	12·00	0·60
Dynamic endurance (min)	2·59	1·53	9·00	0·75
MAL (kg)				
F–K	19·53	8·20	45·45	7·95
F–S	17·22	6·32	36·36	7·59
F–R	15·61	5·68	32·14	7·14
K–S	18·51	7·58	41·48	7·57
K–R	15·18	5·48	29·91	7·09
S–R	14·16	5·13	30·23	7·14

rotation (Hurley and Cattell 1962, Horn 1967) was applied to test an hypothesized factor structure, that is, strength factor and anthropometric factor.

After factors were extracted and rotated, factor scores for each subject on each factor were calculated using regression methods. Factor scores are the estimated values of the common factors. The prediction models for MAL were developed by using the least-squares, stepwise regression technique. Factor scores rather than data-level variables were used as predictors. The model was developed from data collected on 100 of the 146 subjects; validation was accomplished using data collected on the remaining 46.

4. Results

A scree-plot (Cattell 1966 b, 1978, Cattell and Vogelman 1977) based on the eigenvalue of each factor, was used to indicate the amount of variance which can be explained by each factor, and to determine the number of factors selected. As a result, two factors were extracted which accounted for 85% of the variance among seven variables considered: the strength factor, including shoulder, arm, standing back, leg, and composite strength; and the anthropometric factor, including body-weight and abdominal depth. The lifting height (H) was treated as a qualitative variable, and thus a dummy variable with six levels was used in the regression analysis. The resultant model was then simplified by the combination of H (either 0 or 1) and the constant term and was shown as C in equation (3). Each factor's scores and the final predictive model for lifting capacity are shown as follows:

Strength factor (STR):

$$\mathrm{STR} = 0{\cdot}211\mathrm{SHO} + 0{\cdot}212\mathrm{ARM} + 0{\cdot}216\mathrm{BACK} + 0{\cdot}225\mathrm{LEG} + 0{\cdot}226\mathrm{COM} \quad (1)$$

Anthropometric factor (ANT):

$$ANT = 0{\cdot}483BW + 0{\cdot}561ABD \tag{2}$$

Predicted MAL:

$$MAL = C + 0{\cdot}238STR + 1{\cdot}595ANT - 0{\cdot}303F \tag{3}$$

with

STR Strength score
SHO Shoulder strength (kg)
ARM Arm strength (kg)
BACK Back strength (kg)
LEG Leg strength (kg)
COM Composite strength (kg)
ANT Anthropometric score
BW Body weight (kg)
ABD Abdominal depth (cm)
CAP Lifting capacity plus body-weight (kg)
C Constant (2·962, for floor to knuckle height
0·697, for floor to shoulder height
−0·952, for floor to reach height
1·708, for knuckle to shoulder height
−1·232, for knuckle to reach height
−2·705, for shoulder to reach height)
F Frequency of lifting (lifts/min)

Previous models which were developed based on the same data set are in table 3. The present model was validated in the remaining 46 subjects. The model verification of the present study and the comparison with previously developed models are shown in table 4.

5. Discussion

From the experimental data, strength and anthropometric factors were abstracted using factor analysis. Factor analysis explains many variables by showing the structure of each component while seeking to name that component. Therefore, a factor-score-based model is more easily interpreted, and thus more meaningful, than a data-level variable-based model. As shown in the present study, the anthropometric factor represents a worker's body size while the strength factor represents muscular capability and incorporates the five muscular strengths most likely to be encountered in a lifting task.

From the data base examined (73 male and 73 female industrial workers), the distributions of anthropometric scores and strength scores are shown in figures 1 and 2 in which 'percentage accommodation' is the percentage of the experimental sample that has the corresponding score or higher. For example, 75% of the population have strength scores of 53·8 or higher (see figure 2). The best-fit equations are also given for easy access in a computerized design procedure. This information can be used to assess a person's physical characteristics before a job assignment. For example, if an individual's static strength were measured, the strength score for that person could be determined using equation (1). The percentage of this calculated strength score

Table 3. Previously developed models based on the data on Ayoub and co-workers.

	*	Constant term	Sex code †	Weight code ‡	Arm strength (kg)	Age (years)	Shoulder ht. (cm)	Back strength (kg)	Abdominal depth (cm)	Dynamic endurance (min)	(Arm strength)^2	(Age)^2	(Shoulder ht.)^2	(Back strength)^2	(Abdominal depth)^2	(Dynamic endurance)^2
	(*a*)	−32·802	−12·879	11·020	0·065	−0·251	0·557	0·025	2·234	0·799	—	—	—	—	—	—
1 (F–K)	(*b*)	−101·169	—	—	0·105	—	0·804	0·121	2·707	0·640	—	—	—	—	—	—
	(*c*)	−9·065	−7·105	—	0·478	−0·300	—	0·204	—	4·659	$-1{\cdot}818\times10^{-3}$	—	$1{\cdot}818\times10^{-3}$	$-4{\cdot}545\times10^{-4}$	0·066	−0·551
	(*a*)	−66·096	−7·348	5·422	0·084	−0·271	0·654	0·035	2·942	1·185	—	—	—	—	—	—
2 (F–S)	(*b*)	−115·832	—	—	0·044	—	0·863	0·100	3·264	1·370	—	—	—	—	—	—
	(*c*)	−49·441	−3·231	—	0·624	−0·861	—	—	3·493	6·731	$-3{\cdot}182\times10^{-3}$	$7{\cdot}273\times10^{-3}$	$2{\cdot}273\times10^{-3}$	$1{\cdot}364\times10^{-4}$	—	−0·765
	(*a*)	−18·758	−8·842	7·353	0·095	−0·383	0·345	0·031	2·827	0·648	—	—	—	—	—	—
3 (F–R)	(*b*)	−96·625	—	—	0·0064	—	0·710	0·122	3·264	0·134	—	—	—	—	—	—
	(*c*)	−386·815	—	—	0·659	−1·024	4·858	0·035	3·648	8·270	$-3{\cdot}182\times10^{-3}$	$8{\cdot}182\times10^{-3}$	−0·015	—	—	−0·884
	(*a*)	−25·073	−8·387	5·318	0·120	−0·275	0·349	0·048	2·859	0·643	—	—	—	—	—	—
4 (K–S)	(*b*)	−83·473	—	—	0·095	—	0·620	0·111	3·077	0·164	—	—	—	—	—	—
	(*c*)	−67·330	−3·040	—	0·691	−0·982	0·461	—	3·481	6·764	$-3{\cdot}636\times10^{-3}$	$9{\cdot}091\times10^{-3}$	—	$1{\cdot}818\times10^{-4}$	—	−0·904
	(*a*)	−35·997	−8·599	7·851	0·135	−0·227	0·469	0·0082	2·343	0·964	—	—	—	—	—	—
5 (K–R)	(*b*)	−94·300	—	—	0·115	—	0·730	0·078	2·854	0·541	—	—	—	—	—	—
	(*c*)	−88·262	−3·036	—	0·634	−0·914	0·632	—	3·240	8·391	$-2{\cdot}727\times10^{-3}$	$7{\cdot}727\times10^{-3}$	—	$1{\cdot}818\times10^{-4}$	—	−0·904
	(*a*)	−17·018	−8·902	9·251	0·044	−0·269	0·403	0·045	2·150	0·495	—	—	—	—	—	—
6 (S–R)	(*b*)	−96·589	—	—	0·005	—	0·794	0·100	2·746	0·246	—	—	—	—	—	—
	(*c*)	−411·007	—	—	0·438	−0·345	4·605	0·050	6·830	8·217	$-1{\cdot}818\times10^{-3}$	—	−0·014	—	−0·079	−0·870

* (*a*) Ayoub *et al.* (1978); (*b*) Ayoub *et al.* (1986); (*c*) Mital and Ayoub (1980).

† Sex code: 0 for males, 1 for females.

‡ Weight code: 0 if the body-weight is equal to or below the median; 1 if the body-weight is above the median. Median weight: 77·27 kg for males, 61·36 kg for females.

Table 4. Model validation and the comparison with previously developed models.

Height level, *H*	*	R^2	Absolute mean error in MAL (kg)	S.D. of abs. error for MAL (kg)	Max. abs error in MAL (kg)	S.E. of mean for MAL (kg)
1 (F–K)	(*a*)	0·868	6·372	4·415	16·469	0·469
	(*b*)	0·792	6·081	4·789	20·688	0·539
	(*c*)	0·850	3·918	9·377	—	1·073
	(*d*)	—	5·202	3·752	16·010	0·430
2 (F–S)	(*a*)	0·877	5·709	4·286	17·926	0·520
	(*b*)	0·836	5·375	4·621	19·454	0·560
	(*c*)	0·903	0·055	9·000	—	1·132
	(*d*)	—	4·314	3·421	13·945	0·431
3 (F–R)	(*a*)	0·850	7·198	5·272	20·975	0·640
	(*b*)	0·754	7·083	5·471	24·904	0·664
	(*c*)	0·877	1·186	10·582	—	1·309
	(*d*)	—	4·227	3·541	12·722	0·439
4 (K–S)	(*a*)	0·861	6·770	5·221	21·324	0·591
	(*b*)	0·812	6·233	5·263	23·263	0·580
	(*c*)	0·893	2·232	10·045	—	1·027
	(*d*)	—	4·266	0·077	14·950	0·422
5 (K–R)	(*a*)	0·877	5·702	3·766	14·133	0·429
	(*b*)	0·828	6·144	5·095	20·720	0·580
	(*c*)	0·902	3·391	9·400	—	1·068
	(*d*)	—	3·226	2·659	11·314	0·307
6 (S–R)	(*a*)	0·863	5·186	3·543	13·325	0·396
	(*b*)	0·793	5·480	4·670	22·119	0·522
	(*c*)	0·873	5·491	—	—	—
	(*d*)	—	3·499	3·002	12·398	0·342
Overall (Use one model to predict all height levels)	(*d*)	0·924	4·373	3·581	17·761	0·172

* (*a*) Ayoub *et al.* (1978).
(*b*) Ayoub *et al.* (1986).
(*c*) Mital and Ayoub (1980).
(*d*) Present model.

provides information about how this person fits into an industrial population represented by the data base used in this study.

Two task variables (range of lift and frequency of lift) were included in the predictive model. These two variables were found to affect a worker's MAL significantly. Lifting capacity would be changed when the range of lift varied due to involvement of a different muscle group and/or a different vertical distance of movement. From the present data base, the mean MAL is decreasing in the following order: FK, KS, FS, FR, KR and SR. The negative sign in the present model reflects the generally accepted observation that an increase in lift frequency results in a corresponding decrease in lifting capacity (Asfour 1980, Snook 1978). As a result of the inclusion of the two

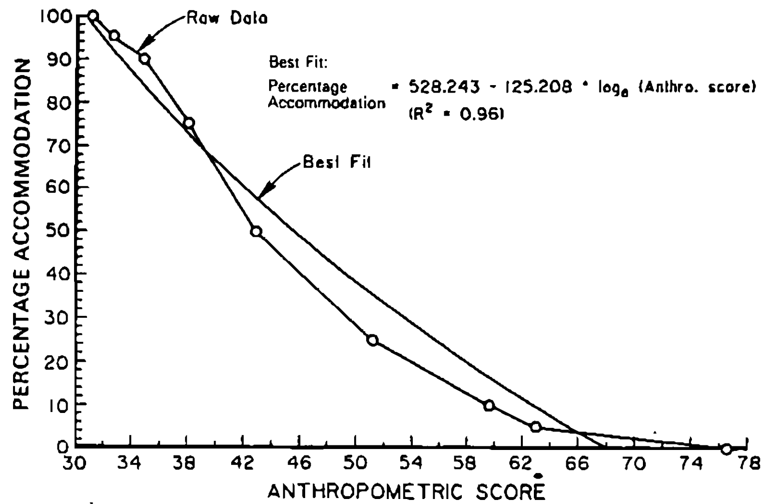

Figure 1. Percentage accommodation for anthropometric scores.

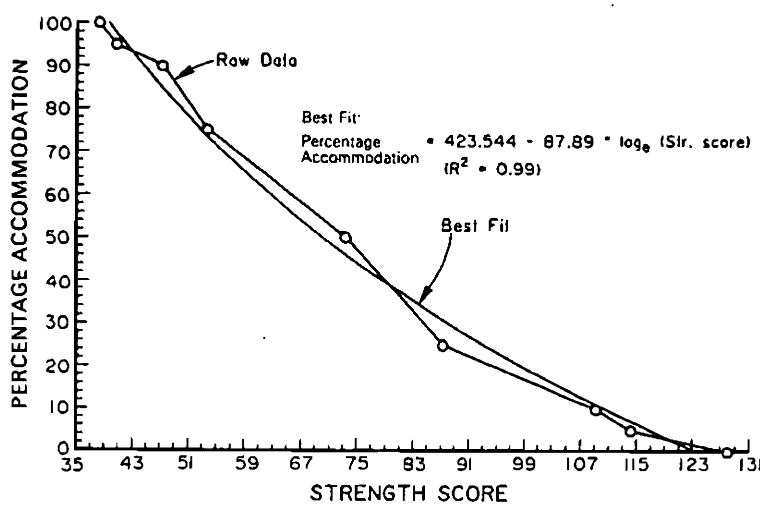

Figure 2. Percentage accommodation for strength scores.

previously mentioned task variables, this MAL model can be applied to any of the six ranges of lift and within indicated frequencies ranging from 2 to 8 lifts/min. Furthermore, since there is no sex variable in the predictive model as shown in the previous model (Ayoub *et al.* 1978), the sensitive problem of gender discrimination is thus avoided.

The limitations of the present model are twofold. First, any application should be within the ranges of the developed model, i.e., frequency of lift (2 to 8 lifts/min), anthropometric score (31·1–76·6), strength score (38·3–128·2), and six ranges of lift. Second, a worker's physical characteristics were correlated only to lifting tasks; consequently, the present model is not applicable to other MMH activities such as lowering, carrying, pushing or pulling.

6. Conclusion

The advantages of the factor-score-based model lie in its providing a more explainable and meaningful structure for determining a worker's MAL, and in its describing a person's physical characteristics by use of simple factors with quantitative scores. A comparison of the present model and previous models developed from the same data base shows that the present model is superior to others in terms of the explainability of the data set (higher R^2 value) and the smaller predicted errors. In addition, the present model allows the use of a single model to predict MAL for all six different ranges of lift and for both genders. The same technique may be applied to other MMH tasks (e.g., lowering, carrying, pushing and pulling) in related fields and more task variables (e.g., wider range of lift) may be incorporated in the model.

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L'adaptation des charges de travail aux caractéristiques physiques de l'individu constitue une méthode efficace pour réduire le risque afférent aux tâches de manutention. Soixante-treize hommes et 73 femmes, tous ouvriers ont servi de sujets. La charge maximum acceptable pour le levage (MAL) a été déterminée par une méthode psychophysique pour chaque combinaison des conditions suivantes: 6 séries de levages (sol à poignets, sol à épaules, sol à atteinte, poignet à épaules, poignet à atteinte et épaules à atteinte), 4 fréquences de levage (2, 4, 6, et 8 levages par mn) et 3 dimensions de caisses (30,48; 45,72 et 60,92 cm). Un modèle à scores factoriels ($R = 0{,}922$) a été élaboré à partir de 100 sujets, pour prédire les MAL individuels et pour décrire leurs caractéristiques physiques en terme de scores de force et de paramètres anthropomorphiques. Le modèle a été validé sur les 46 sujets restants et on a montré qu'il était supérieur aux modèles précédemment développés pour le même type de données.

Das Anpassen der beruflichen Anforderungen an die physischen Charakteristiken einer Person ist eine effektive Methode, um das Risiko, das mit manuellen Materialhandhabungsaufgaben verbunden ist, zu reduzieren. 73 männliche und 73 weibliche Industriearbeiter dienten als Versuchspersonen. Die maximal akzeptierte Last beim Heben (MAL) wurde psycho-physisch während jeder Kombination der folgenden Aufgabenbedingungen bestimmt: 6 Hebeniveaus (Boden–Knöchel, Boden–Schulter, Boden–Ausstrecken, Knöchel–Schulter, Knöchel–Ausstrecken und Schulter–Ausstrecken), 4 Hebefrequenzen (2, 4, 6 und 8 Hebevorgänge/Minute) und 3 Kistengrößen (30·48, 45·72 und 60·96 cm). Ein auf Faktorenwerte gestütztes Modell ($R = 0{\cdot}922$), basierend auf 100 Versuchspersonen, ist in dieser Abhandlung entwickelt worden, um die MAL des Einzelnen vorherzusagen und um seine/ihre physischen Charakteristiken in Form von Kraft- und anthropometrischen Werten zu beschreiben. Die Gültigkeit des Modells wurde für die verbleibenden 46 Versuchspersonen nachgewiesen und es wurde an demselben Datensatz gezeigt, daß dieses Modell besser war als die vorher entwickelten.

職務の要求を作業者の身体的特徴に適合させることは手動荷役作業における危険を低減させるのに有効な方法である。73名の男性と同数の女性工場作業者が被験者となった。最大許容持ち上げ荷重（ＭＡＬ）を次の作業条件の各組み合せ下で精神物理学的に決定した。６つの持ち上げ範囲（床から中手指節関節，床から肩，床から可触範囲，中手指節関節から肩，中手指節関節から可触範囲，肩から可触範囲），４つの持ち上げ頻度（２，４，６，８回／分），３つの箱寸法（30.48，45.72，60.96 cm）．本論文で個人のＭＡＬを予測し，体力と身体計測得点でその身体的特徴を記述するための因子得点基準モデル（R = 0.922）を100名の被験者の結果に基ずいて展開する。本モデルは残りの46名の被験者について実証し，同じデータ・セットから以前に作成したモデルよりも優れていることが示された。

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