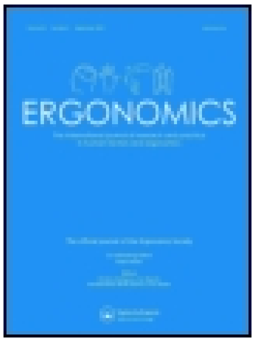

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Comprehensive manual handling limits for lowering, pushing, pulling and carrying activities

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The objective of this study was to develop a set of mathematical models for manual lowering, pushing, pulling and carrying activities that would result in establishing load capacity limits to protect the lower back against occupational low-back disorders. In order to establish safe guidelines, a three-stage process was used. First, psychophysical data was used to generate the models' discounting factors and recommended load capacities. Second, biomechanical analysis was used to refine the recommended load capacities. Third, physiological criteria were used to validate the models' discounting factors. Both task and personal factors were considered in the models' development. When compared to the results from prior psychophysical research for these activities, the developed load capacity values are lower than previously established limits. The results of this study allowed the authors to validate the hypothesis proposed and tested by Karwowski (1983) that states that the combination of physiological and biomechanical stresses should lead to the overall measure of task acceptability or the psychophysical stress. This study also found that some of the discounting factors for the task frequency parameters recommended in the prior psychophysical research should not be used as several of the high frequency factors violated physiological limits.

1. Introduction

The magnitude and cost of lower back injuries have necessitated the need for the development of manual materials handling guidelines. Troup and Edwards (1985) concluded that materials handling injuries are primarily caused by overexertion, 61% of the overexertion injuries are related to the lower back and 74% of the overexertion back injuries are due to lifting, carrying, wielding or throwing, and 15% to pushing and pulling. Research efforts in the area of manual materials handling can be classified by three types of approaches: biomechanical (Chaffin *et al.* 1977, Tichauer 1978, Genaidy *et al.* 1993), physiological (Genaidy and Asfour 1989, Genaidy *et al.* 1990, Asfour *et al.* 1991a,b, and psychophysical (Snook 1978, Ayoub *et al*. 1978, Mital 1984, Snook and Ciriello 1991, Karwowski *et al*. 1992). It is clear that the development of safe guidelines for frequent and infrequent manual handling activities should be based on an integration of the psychophysical, biomechanical and physiological criteria. Few attempts, however, have been made to address this issue.

Waters *et al*. (1993) used the physiological, biomechanical and psychophysical criteria to revise the NIOSH lifting equations. Hidalgo *et al*. (1997) used the three criteria to develop a comprehensive lifting model. However, no guidelines that incorporate the three criteria have been developed for manual lowering, pushing, pulling and carrying tasks. Since many of the industrial handling operations consist of a combination of lifting, lowering, pushing, pulling and carrying activities, there is an urgent need to establish safe limits for all manual handling tasks. The objective of this study was to develop manual materials handling guidelines that incorporate physiological, biomechanical and psychophysical limits. As a result, comprehensive models were established for lowering, pushing, pulling and carrying tasks.

2. Model structure

The comprehensive lifting model proposed by Hidalgo *et al*. (1997) is constructed from the same mathematical format developed by Drury and Pfeil (1975) and adopted in the 1981 and 1991 NIOSH lifting guidelines (Waters *et al.* 1993). The composition of the model is data driven based on the physiological, psychophysical and biomechanical criteria established from research. The format and details of the lifting model's structure and development can be found in Hidalgo *et al*. (1997).

In the present study, comprehensive models for lowering, pushing, pulling and carrying are developed, which also follow the mathematical representation proposed by Drury and Pfeil (1975). These models were built in three stages. Initially, these models were formed based on the psychophysical data established by Snook and Ciriello (1991). Base weights and discounting factor multiplier curves for both male and female populations were generated. Then, the biomechanical approach was used to modify the recommended base weights. Finally, the physiological approach was used to refine the frequency multiplier curves.

The structure of the *lowering model* is defined as follows:

$$LOC = W_{\mathrm{B}} \times H \times V \times F \times AG \times BW \times TD$$

where:

LOC = lowering capacity (kg);
W_{B} = maximum load acceptable to a specified percentage of worker population (kg) and is also a function of level of lowering height (where FK = knuckle to floor, KS = shoulder to knuckle, SR = arm reach to shoulder);
H = multiplier for horizontal distance away from the body with respect to the mid-point between the ankles;
V = multiplier for vertical distance of lower;
F = multiplier for frequency of lower;
AG = age group multiplier;
BW = body weight multiplier; and
TD = task duration multiplier.

For manual pushing and pulling tasks, two different types of forces are included in the pushing and pulling tables. The initial force is the force required to place an object in motion and is a function of the subject's acceleration. The sustained force is the force required to keep an object in motion. The structure of the *pushing model* is defined as follows:

$$PC = F_B \times V \times T \times F \times AG \times BW \times TD$$

where:

- PC = pushing capacity (kg);
- F_B = maximum force acceptable to a specified percentage of worker population (kg);
- V = multiplier for vertical distance from floor to hands;
- T = multiplier for travelled distance;
- F = multiplier for frequency of push;
- AG = age group multiplier;
- BW = body weight multiplier; and
- TD = task duration multiplier.

The structure of the *pulling model* is defined as follows:

$$PLC = F_B \times V \times T \times F \times AG \times BW \times TD$$

where:

- PLC = pulling capacity (kg);
- F_B = maximum force acceptable to a specified percentage of the worker population (kg) and is also a function of type of force (initial or sustained);
- V = multiplier for vertical distance from floor to hands (cm);
- T = multiplier for travelled distance;
- F = multiplier for frequency of pull;
- AG = age group multiplier;
- BW = body weight multiplier; and
- TD = task duration multiplier.

The structure of the *carrying model* is defined as follows:

$$CC = W_B \times V \times T \times AG \times BW \times TD$$

where:

- CC = carrying capacity (kg);
- W_B = maximum weight acceptable to a specified percentage of the worker population (kg);
- V = multiplier for vertical distance from floor to hands;
- T = travelled distance multiplier;
- F = multiplier for frequency of carry;
- AG = age group multiplier;
- BW = body weight multiplier; and
- TD = task duration multiplier.

3. Model development

3.1. *Development of psychophysical criteria*

For the initial formulation of manual materials handling models, each parameter's effect was assessed based on the psychophysical data of Snook (1978) and Snook and Ciriello (1991). The data of Snook and Ciriello was used because it was the only study that established a set of tables based on a large sample size of male and female subjects for lowering, pushing, pulling and carrying tasks. Assuming a normal distribution, the mean and standard deviation for each task studied were used to determine the maximum weights and forces acceptable to 10, 25, 50, 75 and 90% of the industrial population. The validity of this assumption is a function of the sample size of data collected, and may particularly impact the low and high ends of the normal distribution.

In order to calculate the task multipliers for the manual materials handling equations, both the original and revised maximum acceptable weights and forces tables of Snook (1978) and Snook and Ciriello (1991) were used. The Snook and Ciriello (1991) representative load data was used as the base set of conditions as it defines the mean, standard deviation and sample size for a frequency of 1 repetition per minute. This set of representative conditions became the starting point in the Snook and Ciriello (1991) tables to ratio the higher and lower values for that variable. The design value in the table that described the most representative and physically ideal to handle was then set equal to 1·0, and all other values were scaled to that condition. To generate the multipliers, these values were then plotted as a function of the variable. The discounting factor multipliers for the manual materials handling equations are the mathematical coefficients used to reduce the load constant (maximum weight or force) in order to compensate for task characteristics

Table 1. Frequency multiplier for lowering.

	Male	Female	Male	Female
Frequency	$V < 75$		$V > 75$	
0·2	1	1	1	1
0·5	0·925	0·947	0·972	0·889
1	0·825	0·842	0·833	0·778
2	0·738	0·789	0·8	0·748
3	0·686	0·762	0·784	0·73
4	0·657	0·743	0·762	0·723
5	0·634	0·72	0·716	0·724
6	0·612	0·696	0·665	0·727
7	0·596	0·68	0·631	0·718
8	0·582	0·67	0·606	0·698
9	0·568	0·661	0·583	0·676
10	0·555	0·652	0·562	0·652
11	0·541	0·643	0·544	0·63
12	0·525	0·632	0·528	0·611
13	0·508	0·619	0·512	0·596
14	0·49	0·606	0·497	0·581
15	0·47	0·593	0·484	0·567
16	0·45	0·579	0·472	0·556

that are non-ideal. The multipliers for coefficients in each equation are presented in tables 1 – 12.

The multipliers based on worker variables, age and body weight, are derived from the biomechanical data reported in Genaidy *et al.* (1993) and can be found in Hidalgo *et al.* (1997). This data demonstrated that the compressive strength of the lumbar spine decreases significantly as age increases. Furthermore, the compressive strength of the lumbar spine increases with an increase in body weight. The task duration multiplier is based on a physiological study of an industrial population tested by Asfour *et al.* (1991b) and is presented in Hidalgo *et al.* (1997).

All weights and forces are the maximum acceptable weight or force for a given population percentage. The base weight as a function of population percentage for lowering tasks is presented in table 13. Values are provided for both males and

Table 2. Horizontal distance multiplier for lowering.

Distance (cm)	Male	Female	Male	Female
	$V < 75$		$V > 75$	
39	0·785	0·642	0·753	0·81
41	0·76	0·62	0·739	0·799
43	0·738	0·609	0·736	0·796
45	0·719	0·606	0·74	0·8
47	0·701	0·605	0·748	0·806
49	0·682	0·604	0·754	0·811
51	0·662	0·597	0·755	0·812
53	0·639	0·581	0·746	0·804
55	0·611	0·555	0·717	0·775
57	0·577	0·523	0·665	0·718
59	0·539	0·484	0·595	0·638
61	0·497	0·439	0·51	0·541
63	0·453	0·387	0·414	0·433

Table 3. Vertical distance multiplier for lowering.

Distance (cm)	Male	Female	Male	Female
	$V < 75$		$V > 75$	
25	1	1	1	1
35	0·945	0·985	0·939	0·942
45	0·904	0·961	0·885	0·895
55	0·887	0·925	0·839	0·865
65	0·877	0·873	0·799	0·84
75	0·866	0·827	0·773	0·815
85	0·855	0·801	0·76	0·789
95	0·844	0·779	0·749	0·763
105	0·83	0·748	0·737	0·737
115	0·807	0·713	0·726	0·712
125	0·777	0·675	0·714	0·688
135	0·745	0·638	0·703	0·663
145	0·715	0·604	0·692	0·638
155	0·691	0·574	0·678	0·609
165	0·669	0·549	0·656	0·56
175	0·649	0·529	0·629	0·5

females at three levels of lowering: knuckle to floor, shoulder to knuckle and arm reach to shoulder. The base force as a function of population percentage for pushing and pulling tasks is presented in tables 14 and 15. The base weight as a function of population percentage for carrying tasks is presented in table 16.

Table 4. Frequency multiplier for pushing.

Frequency	Initial Male	Initial Female	Sustained Male	Sustained Female
0·002	1	1	1	1
0·016	0·901	0·956	0·894	0·877
0·03	0·854	0·933	0·844	0·818
0·1	0·843	0·919	0·83	0·795
0·2	0·833	0·9	0·813	0·773
0·5	0·813	0·8	0·719	0·727
1	0·792	0·767	0·688	0·682
4	0·542	0·667	0·438	0·545
6	0·557	0·6	0·203	0·455

Table 5. Travelled distance multiplier for pushing.

Distance (m)	Initial Male	Initial Female	Sustained Male	Sustained Female
20	0·732	0·741	0·597	0·637
25	0·6667	0·719	0·552	0·583
30	0·614	0·71	0·511	0·537
35	0·577	0·708	0·474	0·52
40	0·548	0·713	0·44	0·534
45	0·523	0·711	0·409	0·536
50	0·499	0·695	0·383	0·504
55	0·476	0·671	0·36	0·455
60	0·455	0·638	0·341	0·338
65	0·438	0·597	0·326	0·305

Table 6. Vertical height multiplier for pushing.

Height (cm)	Initial Male	Initial Female	Sustained Male	Sustained Female
90	0·988	0·971	0·989	0·983
95	0·996	0·984	0·995	0·992
100	1	0·993	0·999	0·998
105	0·999	0·998	1	1
110	0·993	1	0·999	0·999
115	0·982	0·998	0·996	0·994
120	0·966	0·992	0·99	0·985
125	0·945	0·982	0·983	0·973
130	0·92	0·969	0·972	0·958
135	0·889	0·952	0·96	0·939
140	0·854	0·931	0·945	0·917

3.2. *Development of biomechanical criteria*

Tichauer (1973) expressed the magnitude of lifting stresses in terms of the biomechanical lifting equivalent (BLE). The moment arm in BLE, when holding a load upright, can be approximated by using 8 in. as the thickness of the human body plus half of the length of the load in inches. This sum approximates to the distance of the centre of mass of the load from the lumbar spine. The BLE is defined by the following equation:

$$M = (8 + 1/2\,L) \times W$$

where: M is the biomechanical lifting equivalent; 8 is the approximate distance in inches from the joints of the lumbar spine to the front of the abdomen (a constant for each individual); L is the length (inches) of one side of the object lifted in the sagittal plane; and W is the weight (lb) of the object. In 1978, Tichauer developed bench-

Table 7. Frequency multiplier for pulling.

	Male	Female	Male	Female
Frequency	Initial		Sustained	
0·002	1	1	1	1
0·016	0·898	0·958	0·909	0·864
0·03	0·851	0·938	0·865	0·8
0·1	0·842	0·924	0·852	0·783
0·2	0·83	0·906	0·838	0·76
0·5	0·787	0·813	0·73	0·68
1	0·766	0·781	0·703	0·64
4	0·7	0·738	0·598	0·62
6	0·663	0·696	0·539	0·568

Table 8. Travelled distance multiplier for pulling.

	Male	Female	Male	Female
Distance (m)	Initial		Sustained	
1	1	1	1	1
5	0·93	0·95	0·831	0·972
10	0·878	0·856	0·743	0·877
15	0·845	0·752	0·697	0·75
20	0·785	0·739	0·631	0·696
25	0·717	0·726	0·562	0·655
30	0·657	0·713	0·514	0·625
35	0·614	0·7	0·49	0·604
40	0·577	0·687	0·466	0·587
45	0·547	0·674	0·442	0·565
50	0·524	0·657	0·418	0·532
55	0·505	0·631	0·394	0·492
60	0·491	0·6	0·37	0·446
65	0·485	0·568	0·347	0·393

mark values to classify the stress of a task. These classifications are described in Hidalgo *et al*. (1997).

In order to develop the base weight values for the manual materials handling tasks, the Tichauer BLE equation (1973) was applied as the static analysis of the moment at the L5/S1 intervertebral joint. The compressive stress is the limiting factor for lifting and lowering tasks and the load is assumed to be symmetric, hence the moment in the sagittal plane is computed while the moments in the other two planes are assumed to be equal to zero in the BLE equation. For pushing and pulling, the shear forces are critical; therefore, the Tichauer BLE equation is applied to the transverse or horizontal plane, and the moment in the transverse plane is calculated while the moments in the remaining planes are ignored owing to their minor effects. Carrying is a combination task that consists of the initial lift or lower of the object and then the carry, hence the Tichauer BLE is the moment in the sagittal plane with the moment arm distance defined as resultant of the vertical

Table 9. Vertical height multiplier for pulling.

Height (cm)	Male	Female	Male	Female
	Initial		Sustained	
60	1	1	1	1
65	0·983	0·993	0·993	0·995
70	0·966	0·987	0·984	0·99
75	0·947	0·981	0·974	0·985
80	0·928	0·975	0·962	0·979
85	0·908	0·969	0·949	0·973
90	0·887	0·964	0·935	0·967
95	0·865	0·958	0·919	0·96
100	0·842	0·953	0·901	0·953
105	0·818	0·949	0·882	0·945
110	0·794	0·944	0·862	0·937
115	0·768	0·94	0·84	0·929
120	0·742	0·936	0·817	0·92
125	0·715	0·932	0·792	0·911
130	0·687	0·929	0·765	0·902
135	0·658	0·926	0·738	0·892
140	0·628	0·922	0·708	0·882

Table 10. Frequency multiplier for carrying.

Frequency	Male	Female
0·002	1	1
0·016	0·904	0·842
0·03	0·854	0·769
0·1	0·796	0·768
0·2	0·75	0·769
0·5	0·688	0·731
1	0·667	0·731
4	0·521	0·577
6	0·417	0·3

distance from the lumbar spine to the mid-point of the object and the horizontal distance from the mid-point of the object to the lumbar spine.

To determine the base weight values based on the Tichauer biomechanical criteria for a range of male and female population percentiles, the normal distributions proposed by Hidalgo *et al.* (1997) were established as a function of

Table 11. Travelled distance multiplier for carrying.

Frequency	Male	Female
2	1	1
4	0·871	0·91
6	0·811	0·86
8	0·819	0·849
10	0·894	0·878

Table 12. Vertical height multiplier for carrying.

Height (cm)	Male	Female
75	1	1
80	0·976	0·978
85	0·953	0·957
90	0·929	0·935
95	0·905	0·913
100	0·882	0·892
105	0·858	0·87
110	0·834	0·848

Table 13. Psychophysical and biomechanical base weights (kg) for lowering.

		Biomechanical		Psychophysical	
Moment-F	Pop %	Female	Male	Female	Male
670	5	22·75134	39·0508	30·1	67·6
652·2222	10	22·14765	37·5431	29	63·9
634·4444	15	21·54397	36·0354	28·2	61·5
616·6666	20	20·94028	34·5277	27·6	59·5
598·8888	25	20·3366	33·0234	27·1	57·8
581·111	30	19·73291	31·5123	26·6	56·3
563·3332	35	19·12923	30·0046	26·2	54·9
545·5554	40	18·52554	28·4969	25·8	53·6
527·7776	45	17·92186	26·9892	25·4	52·3
509·9998	50	17·31818	25·46791	25	51
492·222	55	16·71449	23·96021	24·6	49·7
474·4442	60	16·11081	22·45251	24·2	48·4
456·6664	65	15·50712	29·94481	23·8	47·1
438·8886	70	14·90344	19·43711	23·4	45·7
421·1108	75	14·29975	17·92941	22·9	44·2
403·333	80	13·69607	16·42171	22·4	42·5
385·5552	85	13·09238	14·91401	21·8	40·5
367·7774	90	12·4887	13·40631	21	38·1
349·9996	95	11·88501	11·88503	19·9	34·4

the biomechanical lifting equivalent criteria. To calculate the base weight (*W*) for the manual materials handling tasks, the torque (*M*) and the distance (*d*) were fixed. The Tichauer bench-mark value was used as the torque (*M*) for a given population

Table 14. Psychophysical and biomechanical base weights (kg) for pushing.

	Biomechanical		Psychophysical	
Pop %	Female	Male	Female	Male
5	61·88364	110·64	31·5	44·2
10	60·24161	106·37	29·4	41·5
15	58·59959	102·1	28	39·7
20	56·95757	97·83	26·9	38·2
25	55·31555	93·57	25·9	37
30	53·67353	89·28	25	35·9
35	52·0315	85·01	24·2	34·9
40	50·38948	80·74	23·5	33·9
45	48·74746	76·47	22·7	32·9
50	47·10544	72·16	22	32
55	45·46341	67·89	21·3	31·1
60	43·82139	63·62	20·5	30·1
65	42·17937	59·34	19·8	29·1
70	40·53735	55·07	19	28·1
75	38·89532	50·8	18·1	27
80	37·2533	46·53	17·1	25·8
85	35·61128	42·26	16	24·3
90	33·96926	37·98	14·6	22·5
95	32·32724	33·67	12·5	19·8

Table 15. Psychophysical and biomechanical base weights (kg) for pulling.

	Biomechanical		Psychophysical	
Pop %	Female	Male	Female	Male
5	61·88364	110·64	30·7	44·5
10	60·24161	106·37	28·8	41·7
15	58·59959	102·1	27·5	39·9
20	56·95757	97·83	26·5	38·4
25	55·31555	93·57	25·6	37·1
30	53·67353	89·28	24·8	36
35	52·0315	85·01	24	34·9
40	50·38948	80·74	23·3	33·9
45	48·74746	76·47	22·7	33
50	47·10544	72·16	22	32
55	45·46341	67·89	21·3	31
60	43·82139	63·62	20·7	30
65	42·17937	59·34	20	29·1
70	40·53735	55·07	19·2	28
75	38·89532	50·8	18·4	26·9
80	37·2533	46·53	17·5	25·6
85	35·61128	42·26	16·5	24·1
90	33·96926	37·98	15·2	22·3
95	32·32724	33·67	13·3	19·5

percentile. The moment distances (*d*) used in the calculations are values representative of common industrial tasks. For example, the moment arm is defined for the pushing/pulling task as the vertical distance from the hands to the L5/S1 joint and is calculated from anthropometric measurements to be 12 cm for males and 12·5 cm for females. For carrying, the resultant of (1) horizontal distance defined for lifting and lowering (34 cm), and (2) vertical distance used for pushing and pulling

Table 16. Psychophysical and biomechanical base weights (kg) for carrying.

	Biomechanical		Psychophysical	
Pop %	Female	Male	Female	Male
5	21·36866	36·82	31·6	66·1
10	20·80166	35·4	30·4	62·1
15	20·23467	33·48	29·5	59·4
20	19·66767	32·56	28·9	57·3
25	19·10067	31·14	28·3	55·4
30	18·53368	29·71	27·8	53·8
35	17·96668	28·29	27·3	52·2
40	17·39968	26·87	26·9	50·8
45	16·83269	25·45	26·4	49·4
50	16·26569	24·01	26	48
55	15·69869	22·6	25·6	46·6
60	15·1317	21·17	25·1	45·2
65	14·5647	19·75	24·7	43·8
70	13·9977	18·33	24·2	42·2
75	13·43071	16·91	23·7	40·6
80	12·86371	15·48	23·1	38·7
85	12·29671	14·06	22·5	36·6
90	11·72972	12·64	21·6	33·9
95	11·16272	11·21	20·4	29·9

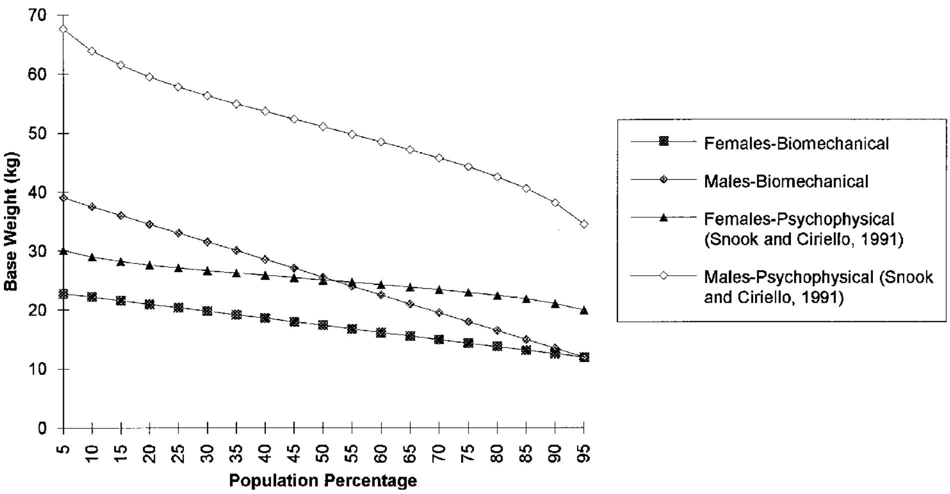

Figure 1. Comparison of base weight data between present study and Snook and Ciriello (1991) for lowering tasks.

(12 cm for males, 12·5 cm for females) was used as the moment arm for the moment computation in the sagittal plane.

As an example, to calculate the base weight for a 50% population percentile male for the lowering task, the following equation is solved for W:

$$M = W \times d$$

where: M is the moment defined by the Tichauer guidelines, 84·8 Nm for a 50% population percentile male; W is the base weight, the unknown; and d is the

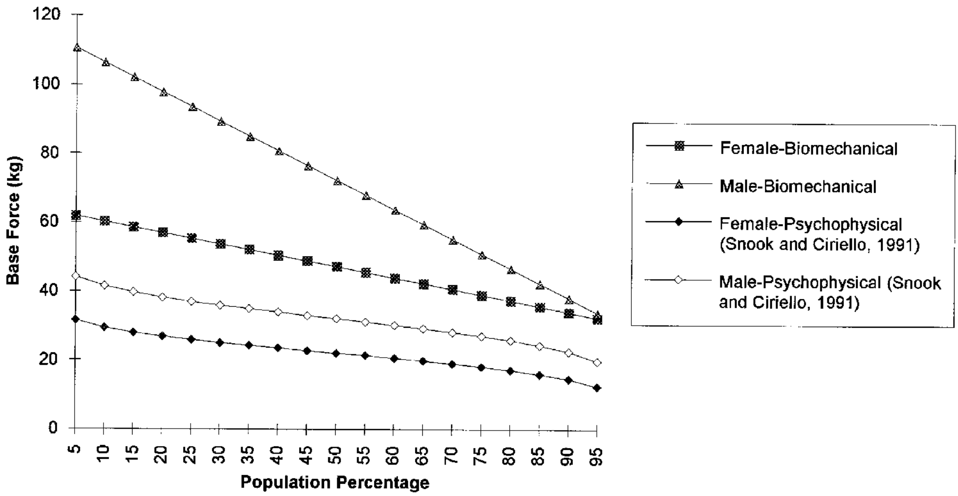

Figure 2. Comparison of base weight data between present study and Snook and Ciriello

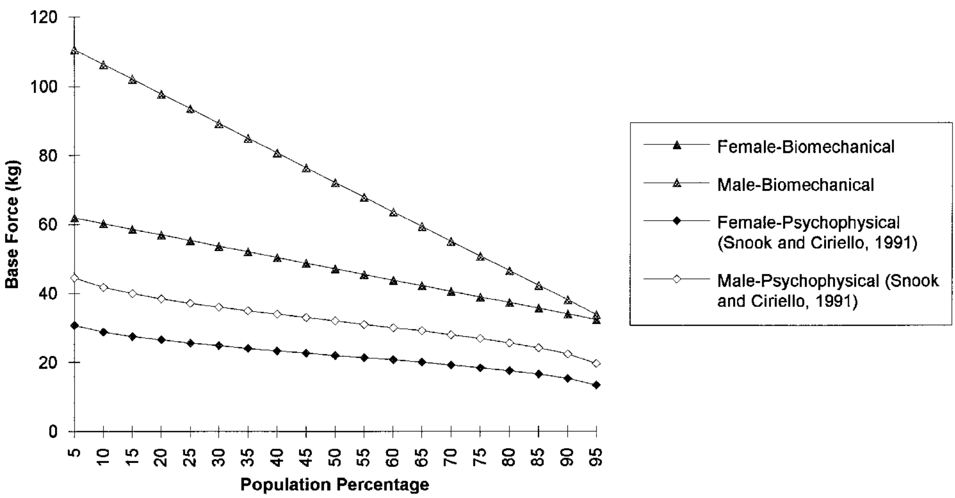

Figure 3. Comparison of base weight data between present study and Snook and Ciriello (1991) for pulling tasks.

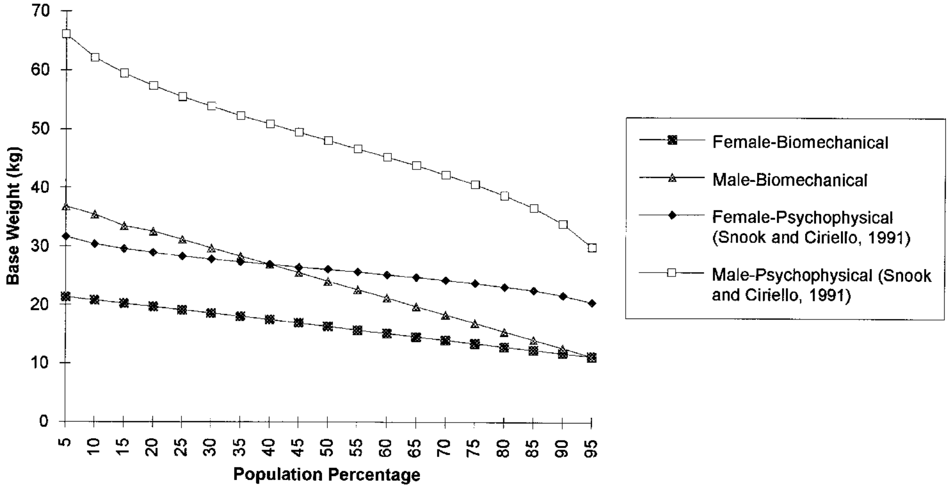

Figure 4. Comparison of base weight data between present study and Snook and Ciriello (1991) for carrying tasks.

horizontal distance, 34 cm. Solving this equation yields a base weight (W) of 25·5 kg. The base weights satisfying the Tichauer guidelines for males and females for various population percentiles as well as the psychophysically derived recommended weights are presented in figures 1 – 4. The biomechanically derived weights are also presented in tables 13 – 16.

3.3. *Development of physiological criteria*

For manual materials handling tasks at frequencies greater than 4 times/min, the physiological methodology defines the task limits (Genaidy 1983, Karwowski and Yates 1986, Waters *et al.* 1993). Metabolic energy expenditure and heart rate are the physiological measurements that are used most often to determine the maximum task intensity that can be continuously withstood without accumulating an excessive amount of physical fatigue. Garg *et al.* (1978) developed a model to predict metabolic expenditure rates for manual materials handling jobs. The model is based on the assumption that a job can be divided into simple tasks, activity elements, and the average metabolic energy rate of the job can be determined by summing the energy expenditures of the simple tasks divided by the time duration of the job. After the job is divided into simple task elements, a metabolic cost to each task is assessed based on force, distance, frequency, posture, technique, gender, body weight and time for each task. Then, an energy requirement to perform a given task is predicted. The average metabolic energy expenditure for the job is equal to the sum of the energy demands of all the tasks and the maintenance of body posture over the time duration.

Physiological capability is the factor that limits continuous lifting tasks at frequencies greater than 4 times/min (Genaidy 1983, Waters *et al.* 1993). Several studies have investigated endurance time and physiological responses to prolonged lifting tasks. Asfour (1980) concluded that at a high frequency of lift (6 times/min or higher) individuals tend to overestimate their lifting capacity using the psychophysical approach over a work duration of less than 1 h. Therefore, it is expected that for high frequencies the discounting factor frequency multipliers developed from the psychophysical approach may overestimate worker capability. In order to refine the frequency multipliers for the comprehensive manual materials handling models for lowering, pushing, pulling and carrying developed in this study, the energy expenditures for these tasks were calculated using the model developed by Garg *et al.* (1978). The predicted energy expenditures were then compared against the physiological fatigue limits that were based on the Asfour *et al.* (1991b) study. The 1 h task duration period was used for the physiological fatigue limit values as the manual materials handling equations account for the effects of task duration as a discounting factor. In the absence of physiological fatigue limit data for lowering, pushing, pulling and carrying, the physiological fatigue limit data for lifting generated by Asfour *et al.* (1991b) was used. This data, which tested industrial workers performing lifting tasks, was preferred over physiological fatigue limit data developed from treadmill and bicycle ergometer studies. The physiological fatigue limits establish maximum oxygen consumption values as a function of task frequency, load and endurance time, hence if the Garg *et al.* (1978) energy expenditure model predicts a higher value for a given task than the physiological fatigue limit defines, the psychophysical derived frequency multipliers for the task must be revised.

In order to utilize the Garg energy expenditure equations, several assumptions were made. The following male and female body weights were used for all tasks. For males, an average weight of 75 kg was used, and for females a weight of 62 kg was used. For lowering, a stoop lower posture was assumed as it yields an energy expenditure approximately midway between the arm lower and squat lower positions (Garg 1976). The weight of load lowered was 25·5 kg, which represents the load that 50% of the population can lower based on the biomechanical analysis. The task energy expenditure was calculated for frequencies of 3 – 16 repetitions/minute. The task and position energy expenditures were then summed to obtain the total energy for the task. In order to determine the adequacy of the frequency multiplier developed from the pscyhophysical approach, the total job energy expenditure was then divided by the physiological fatigue limit criteria. If the ratio of the Garg (1976) predicted energy expenditure to physiological fatigue limit value exceeded 1·2, the frequency multiplier derived from the psychophysical approach was judged to be inadequate for the given frequency and must be revised by adjusting it downward by the percentage which the ratio exceeded the 1·2 value. The safety factor, 1·2, was chosen to provide a margin of safety of 0·20 as this value is commonly used in industry. For lowering, none of the ratio values exceeded the 1·2 criteria. Therefore, the lowering frequency multiplier (table 1) was validated using the physiological approach.

For the pushing/pulling task, the appropriate Garg (1976) equations were used to predict the energy expenditure for the push/pull. This equation defines the energy expenditure for a 81 cm push/pull that most closely approximates the height of push/pull used in the Snook and Ciriello (1991) study. The load pushed/pulled was equal to the 50th population percentile for pushing derived for the psychophysical approach, 22·0 kg for females and 32 kg for males. A travelled distance of 30·5 m was assumed to correlate with the base set of conditions described in the Snook and Ciriello (1991) study. The speed of walking while pushing/pulling the load was assumed to be equal to the speed of walking without the load and was set at 4·4 km/h. The analysis showed that for frequencies of 4 and 6 repetitions/min (male and female) the ratio exceeds the 1·2 criteria by over 100%. Therefore, because they exceed the physiological work capacity limit, these frequencies for pushing/pulling are not recommended. For all other frequencies, the ratio is less than 1·2; therefore, the frequency multipliers for pushing/pulling are validated by the physiological approach.

For carrying, the load was assumed to be held at the waist or against the thighs. A travelled distance of 4·3 m was assumed to correlate with the base set of conditions described in the Snook and Ciriello (1991) study. The load carried was representative of the 50th population percentile as derived from the biomechanical approach, 24 kg for males and 16·3 kg for females. The speed of walking while pushing/pulling the load was assumed to be equal to the speed of walking without the load and was set at 4·4 km/h. For frequencies of 4 and 6 repetitions/min (male and female) the ratio calculated exceeds the 1·2 criteria by over 100%. Therefore, because they exceed the physiological work capacity limit, these frequencies for carrrying are not recommended. For all other frequencies, the ratio is less than 1·2, and the frequency multipliers for carrying are validated by the physiological approach.

4. Comparison to previous guidelines

The only guidelines for lowering, pushing, pulling and carrying tasks were developed by Snook in 1978 and by Snook and Ciriello in 1991. The Snook and Ciriello study (1991) established tables that describe the maximum acceptable weights and force for lifting, lowering, pushing, pulling and carrying tasks, revising the guidelines established in the 1978 study. After reviewing their earlier study, Snook and Ciriello (1991) conducted four new manual materials handling experiments to study lifting, lowering, pushing, pulling and carrying tasks. The experiments run to obtain the data were conducted using psychophysical methodology. The method requires that the subject is motivated by incentive and selects the maximum weight for load or force that can be managed for a projected 8-h workday, based on the subject's perceived feelings of exertion. The major assumption of the psychophysical method is that given an adjustment time of 40 min, a person is capable of predicting the maximum weight or force he/she would be willing to handle for an 8-h period.

The results of the 1991 experiments were then integrated with the results of seven experiments obtained previously from the Snook 1978 study. The mean and standard deviation for each task was used with the normal distribution to yield the maximum acceptable weights and forces to 10, 25, 50, 75 and 90% of the industrial population. The revised tables were established based on a sample size of 119 subjects, 68 males and 51 females. Snook developed this data using psychophysical methodology and it is important to note that some of the weights and forces found in the tables exceed the recommended physiological criteria when performed on a continual basis for 8 h or more.

A comparison of the base weights and forces for lowering, pushing, pulling and carrying developed from the Snook and Ciriello (1991) psychophysical approach and the base weights and forces generated from the biomechanical analysis performed in this study are described in figures 1–4. For lowering and carrying, the base weights established from the biomechanical analysis are significantly less than the weights generated from the psychophysical analysis (Snook and Ciriello 1991). However, these results support the study by Karwowski (1983) which asserts that the combination of biomechanical and physiological stresses approximate the psychophysical stress. Therefore, the biomechanical limits should be lower than the psychophysical limits. Karwowski and Yates (1986) concluded that the psychophysical method fails to produce reliable data at frequencies of lift higher than 6 lifts min^{-1}. Also, since the biomechanical limits are designed to protect the integrity of the lower back, being more conservative, the base weights derived from the biomechanical analysis for lowering and carrying replace the base weights obtained from the Snook and Ciriello (1991) psychophysical study as the recommended base weight for the comprehensive models. For pushing and pulling, the base forces determined from the biomechanical approach are significantly higher than the forces generated from the psychophysical approach due to the short moment arm (12 cm males, 12·5 cm females). Since the biomechanical forces are on average approximately two to three times higher than the psychophysical forces, it is concluded that the Karwowski (1983) hypothesis is valid for tasks involving compressive forces only, namely, lifting, lowering and carrying. For pushing and pulling, provided that the shear forces are dominant, the validity of the Karwowski hypothesis is not known. Therefore, for the pushing and pulling tasks the psychophysically-derived base forces will be used for the comprehensive models' base recommended forces (tables 14 and 15).

The discounting factor data was developed from Snook (1978) and Snook and Ciriello (1991). To generate the multipliers, the value in the table that represented the most representative and physically ideal to handle was set at equal to 1·0, and all other values were scaled to that condition. Therefore, for all task multipliers with the exception of frequency, the values presented in tables 1 – 12 are derived directly from the Snook (1978) and Snook and Ciriello (1991) research. However, the frequency discounting factors initially developed from this research were revised based on the physiological analysis performed using the Garg (1976) energy expenditure equations and physiological fatigue limit criteria based on the research of Asfour *et al.* (1991b). The frequency discounting factors for 4 and 6 repetitions/minute for pushing, pulling and carrying tasks, initially developed from the psychophysical research presented in tables 4, 7 and 10, respectively, are not recommended for use in the model's equations as they violate the physiological analysis criteria.

5. Discussion

In this study, manual materials handling models that predict recommended allowable loads were developed for lowering, pushing, pulling and carrying. To create the models' recommended base loads and discounting factor multipliers, a three-stage approach was employed. Initially, the model-recommended base loads and multipliers were built upon the Snook and Ciriello (1991) data, which established maximum weights and forces based on the psychophysical approach. Second, the base loads for lowering and carrying were revised based on Tichauer's (1973) BLE equation to achieve a safe load standard based on the biomechanical integrity of the lower back. For pushing and pulling it was demonstrated that because of the short moment arm, the biomechanically derived forces were significantly higher than the psychophysically derived forces. Therefore, it is concluded that the hypothesis of Karwowski (1983) is valid for tasks in which the compressive forces are critical but is not appropriate for tasks in which the shear forces are critical. Finally, each model's frequency multiplier was tested for physiological feasibility based on Garg (1976) energy expenditure equations and physiological fatigue limits developed by Asfour *et al.* (1991b).

The comprehensive manual materials handling guidelines for lowering, pushing, pulling and carrying developed in this study were based on manual materials handling research, which has concentrated primarily on the lifting task. In the absence of extensive research for lowering, pushing, pulling and carrying tasks, the data and methodology for lifting has been applied where necessary. In order to validate the results of this study, the guidelines must be tested in an industrial setting.

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