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Evaluation of the ability of power to predict low frequency lifting capacity

PATRICK G. DEMPSEY†*, M. M. AYOUB‡ and PETER H. WESTFALL§

†Liberty Mutual Research Center for Safety and Health, 71 Frankland Road, Hopkinton, Massachusetts 01748, USA

‡Department of Industrial Engineering and §Department of Information Systems and Quantitative Sciences, Texas Tech University, Lubbock, Texas 79409, USA

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An experiment was conducted to examine the role that maximal lifting power has in predicting maximum acceptable weight of lift (MAWL) for a frequency of one lift per 8 h. The secondary aim of the study was to compare the ability of power to predict MAWL to previously used measures of capacity including two measures of isometric strength, five measures of isokinetic strength, and isoinertial capacity on an incremental lifting test. Twenty-five male subjects volunteered to participate in the experiment. The isometric tests involved maximum voluntary contractions for composite lifting strength at vertical heights of 15 and 75 cm. Peak isokinetic strength was measured at velocities of 0.1, 0.2, 0.4, 0.6 and 0.8 m s^{-1} using a modified CYBEX® II isokinetic dynamometer. Isoinertial lifting capactity was measured on the X-factor incremental lifting machine and peak power was measured on the incremental lifting machine by having subjects lift a 25 kg load as quickly as possible. The results indicate that peak isoinertial power is significantly correlated with MAWL, and this correlation was higher than any of the correlations between the other predictor variables and MAWL. The relationships between the isokinetic strength measures and MAWL were stronger than the relationships between the isometric measures and MAWL. Overall, the results suggest that tests used to predict MAWL should be dynamic rather than static.

1. Introduction

A recent antecedent-oriented analysis of events preceding a large sample of work-related injuries and illnesses (Murphy *et al.* 1996) indicated that injuries attributed to manual materials handling (MMH) accounted for 32% of the claims and 36% of the costs. The sample represented claims reported during 1990 to the Liberty Mutual Insurance Company, which provides workers' compensation coverage to approximately 10% of the private insurance market in the USA. Injuries attributed to MMH were the single largest class of claims. Preventing such injuries has the potential to result in a significant reduction in pain and suffering; economic losses by employers, employees, and insurance carriers; and the costs of goods and services.

1.1. *Approaches to the control of MMH-related low-back pain and injuries*

The three basic approaches to the control of low-back pain and injuries in industrial settings are job design, medical screening/job placement, and education/training.

*Author for correspondence.

These approaches are frequently employed to reduce the frequency and severity of low-back disorders in industry, with more emphasis on the first two techniques. The ergonomic approach of job design is the most effective method, but is only partially effective (Snook *et al.* 1978).

The literature does not provide strong evidence that preplacement medical examinations (e.g. X-rays) are successful (Rowe 1983, Gibson 1987, Bigos *et al.* 1992), but replacement strength and fitness testing has been used and is supported by the literature (Chaffin and Park 1973, Cady *et al.* 1979, Ayoub *et al.* 1983). Strength and fitness testing appears to be the most effective method of preplacement testing (Snook 1987).

Training encompasses both strength and fitness training as well as education in the proper methods of lifting and back care. There are no strong objective epidemiological data to support such programmes nor to discourage them. The 'effectiveness of training as a means of preventing MMH-related back injuries is confused, at best' (Kroemer 1992:1130). Few, if any, published studies strongly support the use of education as an effective prophylactic measure.

While job design is the most powerful and effective control tool available, it has not alleviated the problem of MMH-related injuries. Given the ineffectiveness of training and education, preplacement tests appear to be the most attractive supplement to job design techniques. The research reported here was aimed at furthering the knowledge of the effectiveness of various types of preplacement strength testing.

1.2. *Preplacement testing for MMH tasks*

The ergonomics community has developed many preplacement screening techniques and methods to predict the 'safe' lifting capacity of individuals in an attempt to stem the incidence and severity of MMH-related musculoskeletal injuries. However, a disproportionate number of these methods have relied on isometric strength testing, capacity and modelling (Chaffin and Park 1973, Garg and Chaffin 1975, Ayoub *et al.* 1978, Mital and Ayoub 1980, Anderson and Catterall 1987, Rühmann and Schmidtke 1989). The 'Work practices guide for manual lifting' developed by NIOSH and its revision were primarily developed with static strength considerations and static biomechanical models (NIOSH 1981, Waters *et al.* 1993).

Dempsey (1996) provides a review of the literature reporting results of investigations of preplacement tests for MMH tasks, in particular lifting tasks. The review indicates that dynamic measures of lifting capacity have been found to be better predictors of lifting capacity than static measures. The review clearly indicates that isokinetic testing at various velocities and several types of isoinertial tests are superior to isometric testing.

Although some earlier research was restrained by technological limitations and the high cost and difficulties associated with dynamic measurements, these limitations are currently not as restrictive as in the past. Several isokinetic techniques have evolved, but even isokinetic tests place an unrealistic limitation, constant speed of motion, on a test. The current state of technology allows almost any dynamic measure to be used in research. Ideally, isometric and isokinetic techniques should be replaced by isoinertial-based tests that are representative of the kinematic and kinetic nature of MMH tasks and that can predict the risk of future injury.

1.3. *Human muscle power*

Early in this century, Taylor (1911:54) was performing experiments to further investigate 'what fraction of a horse-power a man-power was'. Taylor (1911) was more interested in determining maximum daily work rates than in safe lifting limits. The trend continued with an attempt to understand power output during elemental motions in order to understand humans' capacity to do work, the fatigue potential of tasks, and perhaps to use power capacity as a preplacement technique (Koepke and Whitson 1940).

Power has been studied with considerable rigour by exercise scientists seeking to determine the sources of performance variation for various athletic events (Margaria *et al.* 1996, Coyle *et al.* 1979, Gregor *et al.* 1979, Dowling and Vamos 1993). Many athletic contests require short, but very powerful, bursts of work to be performed. Additionally, power can provide more information than other performance measures for a task. For example, two individuals may be capable of jumping to the same height, but the heavier individual is more powerful (Harman 1991).

Examples of activities requiring powerful bursts include jumping, sprinting, weightlifting, and rowing. Like the aforementioned athletic activities, MMH tasks, particularly lifting, require that powerful bursts of work be performed in the early stages of the task. Danz and Ayoub (1992) measured peak vertical forces applied to the load during a floor-to-knuckle lift. The results indicated that the peak forces applied to the load were on average between 2 and 3.5 times the magnitude of the load, depending on lifting speed. This study supports the notion of the rapid development of large forces during lifting activities.

An early ergonomic investigation of power was concerned with space travel. Slote and Stone (1963) performed a biomechanical analysis of elbow flexion to determine the power capabilities of the elbow under weightlessness conditions. This study has been cited mainly for its kinematic equations describing a ballistic movement, rather than the power aspects investigated.

Grieve (1984) investigated the effects of various whole-body postures on the ability to generate power with a pulling motion. That author cited an example in which the results were applied to the starting of an outboard motor, concluding that the power output of a single movement is relevant to matching the task to the human operator.

More recently, the power exerted during an isoinertial lift using the X-factor lifting machine has been described and summarized (Bryant *et al.* 1990, Stevenson *et al.* 1990). The first phase of the isoinertial lift was described as 'a powerful pulling phase', which included the maximal power exerted at any point in the lift (Stevenson *et al.* 1990 : 161). Bryant *et al.* (1990) performed a principal component analysis using various time and displacement relationships as well as measures of force and power. The two factors explaining the greatest portion of the variance included time and displacement at maximum power, and maximum power and power at second maximum force, respectively, as well as several other related variables. These studies support the notion that power plays a role in lifting capacity.

One rationale for investigating power, rather than simply strength, is that lifting requires exertion of forces at varying velocities. While isometric strength is appropriate for the pre-liftoff phase of a lift; it becomes a less appropriate measure of capacity as the velocity of the load begins to increase. During lifting, it is necessary to exert considerable forces in the early stages of the lift during which the velocity of the load continues to increase. During this phase, the success of the lift may be determined by the ability to increase force generation as the velocity of muscle contraction increases. Thus, even isokinetic strength testing may not be a completely appropriate means of testing MMH capacity.

1.4. *Specific aims*

In 1991, the National Institute for Occupational Safety and Health (NIOSH) convened a panel of experts to determine the nature of research needed to prevent occupational musculoskeletal injuries. One conclusion was that there is a need for research to 'concentrate on improving those worker evaluation methods that are directly related to specific job requirements, as opposed to generic physical performance tests of strength, flexibility and endurance' (NIOSH 1992: 14). This statement implies that preplacement tests for MMH tasks need to be *directly related* to the capacity to safely perform MMH tasks and subsequently to future incidents of low-back disability. The general goal of this research was to evaluate and compare several worker evaluation methods.

The first specific aim of the proposed research was to empirically investigate the role that power may have in determining an individual's lifting capacity for a frequency of one lift per 8 h. It was hypothesized that power plays a greater role in lifting capacity than previously used measures, particularly isometric strength.

The second specific aim was to elucidate the relative role that strengths, measured by various techniques, have in predicting lifting capacity. Isometric strength, isokinetic strength, power assessed through an isoinertial technique, and isoinertial lifting capacity measured on an incremental lifting machine were related to maximum acceptable weight of lift (MAWL) for a frequency of one lift per 8 h through statistical methods.

2. Methods

2.1. *Subjects*

Twenty-five male subjects volunteered to participate in the study and were paid for their participation. Subjects were given a medical examination by a physician prior to participation to ensure their fitness for the experimental tasks. The sample characteristics are summarized in table 1.

2.2. *Apparatus*

2.2.1. *Isometric and isokinetic apparatus*: Isometric strength and isokinetic strength were measured using a CYBEX® II isokinetic dynamometer (Cybex, Bay Shore, NY), cables, and handles guided by linear bearings. The mid-points of the handles were 35.5 cm apart, which is equal to the separation of the handles used for the psychophysical procedure. The centre of the handles had a vertical range of 15 to 95 cm.

Table 1. Anthropometric characteristics of subject sample ($n = 25$).

Variable	Mean	SD	Minimum	Maximum
Age	21.64	2.46	18	26
Height (cm)	179.63	5.81	170.2	195.6
Weight (kg)	78.45	13.52	61.2	112.5

SD = standard deviation.

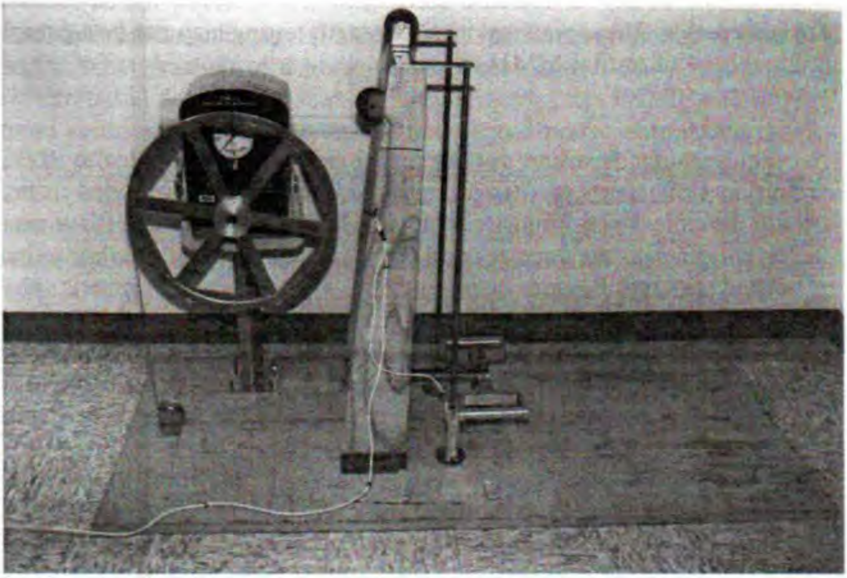

Figure 1. Illustration of the isometric and isokinetic apparatus.

The isometric/isokinetic apparatus is shown in figure 1. A custom-made aluminium wheel was attached to the isokinetic dynamometer. By attaching a cable to the wheel, guiding the cable with pulleys, and attaching the cable to the handles, the isokinetic dynamometer was converted from rotary to linear motion. A load cell (Model 1350-0600, Houston Scientific International, Houston, TX) was attached between the cable and the handles to measure force.

A combination displacement and velocity transducer (Model 1150-125, Houston Scientific International, Houston, TX) was affixed to the apparatus. The velocity (m s^{-1}) was obtained by dividing the voltage output by the coefficient supplied by the manufacturer. The velocity transducer was used so that a digital readout could be used to set the various velocities, rather than using the less accurate analogue readout on the control box of the CYBEX®. The signal from the transducer was fed to an analogue-to-digital (A/D) board. This apparatus was also used for collecting the isometric strength data, which was accomplished by placing the handles at the proper vertical height (15 or 75 cm) and setting the velocity of the dynamometer to zero.

Calibrations were performed for the load cell and displacement transducer using linear regression to predict the force and displacement associated with the voltages from the respective transducers. The r^2 values were above 0.999, indicating very linear relationships.

2.2.2. *Isoinertial apparatus*: The isoinertial apparatus consisted of the X-factor incremental lift machine fitted with a load cell (Model 1350-0600) to measure vertical forces applied to the handles, a velocity transducer to measure velocity directly and a displacement transducer to measure the vertical location of the handles. The isoinertial apparatus shown in figure 2 was used for the incremental lifting test and the isoinertial power measurements. The velocity and displacement transducers were those used with the isokinetic apparatus. The calibration models indicated that the force and displacement transducers were very accurate (r^2 values were above 0.999).

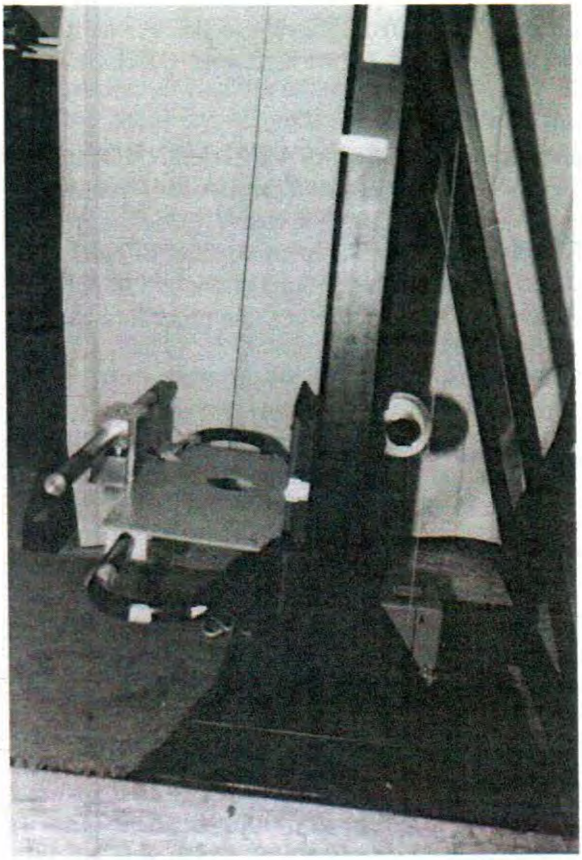

Figure 2. Illustration of the isoinertial apparatus.

2.2.3. *Psychophysical apparatus*: The apparatus used for the psychophysical assessments consisted of a $30.5 \times 30.5 \times 30.5$ cm wooden box with handles, lead weights of various shapes and sizes, and a stationary 76 cm high shelf. Each handle added 2.5 cm in the frontal plane; thus the centre of the handles were 35.5 cm apart. The height of the shelf (76 cm) represents knuckle height.

2.2.4. *Data acquisition hardware and software*: A Beckman R511A Dynograph Recorder, Beckman amplifier, Beckman 461D preamplifier and a Beckman 4803 strain gauge coupler (Beckman, Fullerton, CA) provided the excitation and amplification for each of the load cells used. Shielded coaxial cables connected the amplifiers to the computer interface board. The interface board was attached to a Macintosh IIx (Macintosh, Cupertino, CA) computer equipped with a National Instruments (Austin, TX) Lab-NB 12-bit A/D conversion board. The displacement and velocity transducers were also wired to the interface board.

Data acquisition was controlled by LabView® (National Instruments, Austin, TX). The software controlled sampling rate and length of data collection. The sampling rates used were 25 Hz for the static measurements, 50 Hz for the isokinetic measurements, and 100 Hz for the isoinertial power measurements. The digital signals were converted to appropriate units (N, m s^{-1}) by LabView® using the calibration coefficients obtained from the regressions. Power (vertical) was calculated by LabView® as the dot product of the force and velocity measurements.

2.3. *Procedure*

The testing was divided into four sessions with at least 24 h between sessions. Session 1 involved determination of MAWL for a frequency of one lift per 8 h. The starting load was alternately light (2–18 kg) or heavy (32–45 kg) (Ciriello *et al.* 1990). Subjects were read instructions specific to a frequency of one lift per 8 h (Ciriello and Snook 1983), and performed two repetitions of the psychophysical procedure. If the values were not within ± 15% of each other, the procedure was repeated on another day (Snook and Ciriello 1991).

The remainder of the first session involved practice with the X-factor isoinertial lifting machine. Subjects lifted the 25 kg carriage to a height of at least 183 cm once per minute for 15 min. Subjects then practised lifting the carriage as quickly as possible once per two minutes for 20 mins. After a 10 min rest period, subjects practised the incremental lifting test. Subjects lifted the 25 kg carriage to a height of 183 cm. The experimenter added 4.5 kg increments until subjects could not lift the load to 183 cm.

Isoinertial power measurements (ISOPOW) were taken during the second session. Subjects were instructed to lift the 25 kg carriage as quickly as they could safely. Subjects performed three repetitions separated by 5 min rest periods. In some cases, a fourth trial was run. Some subjects appeared to need a 'warm-up' trial, indicated by a relatively low value on the first trial. For these subjects, the fourth trial replaced the first. The score for the trail was the peak power at any point during the lift. If one of the three trials appeared to be significantly lower than the other trials, another trial was run. Following a 10 min rest period, subjects performed the X-factor incremental lifting test (XFAC) and their scores were recorded. The score on the test was the largest load the subject lifted to at least 183 cm.

The third session involved practising the isometric and isokinetic strength measurements. Subjects practised the isometric strength measurements at 15 cm (IMET15) and 75 cm (IMET75) for three trials each separated by 3 min rest periods. Subjects also practised the isokinetic strength measurements at speeds of 0.1 (IKIN0.1), 0.2 (IKIN0.2), 0.4 (IKIN0.4), 0.6 (IKIN0.6) and 0.8 m s^{-1} (IKIN0.8) for three trials each separated by 3 min rest periods.

The fourth session involved collecting the isometric and isokinetic strength data. The isometric data were collected first. The order of collecting IMET15 and IMET75 was alternated. The experimenter had subjects build up to their maximum voluntary contraction (MVC) over a period of approximately 2 to 3 s. Once subjects achieved what appeared to be their MVC (based on the analogue torque meter on the CYBEX®) the experimenter initiated the collection of 75 samples over 3 s. The strength datum used was the mean value of the 75 samples. If any sample was outside ± 10% of the mean value, the test was re-run (Caldwell *et al.* 1974). Two consecutive exertions within ± 15% of each other were considered to be acceptable, and the mean of these two values was used as the datum. Subjects were given 5 min rest between all exertions.

For the IMET15 exertions, subjects were told to use a posture as similar as possible to the posture they adopted at the origin of the lifts performed for the psychophysical procedure. Most subjects tended to use postures with at least partially bent knees even though no instructions were given on lifting technique.

The isokinetic testing followed the isometric testing. The five velocities were presented in random order. Owing to a lack of instructions and protocols for isokinetic testing in the literature, subjects completed three repetitions at each velocity. Subjects were instructed to exert maximum force on the handles until the handles reached a height of 95 cm, at which point the apparatus restricted the handles from moving any further. The peak force value during the trial was used as the datum for that trial. If one datum appeared to be considerably lower than the other two, the trial was repeated. There was a 5 min rest period between all exertions.

2.4. *Statistical analyses*

As mentioned earlier, two repetitions of each isometric test were performed, three repetitions of each isokinetic test were performed, and three repetitions of ISOPOW were performed. For the correlation and latent variable structural equation model analyses, a single datum for each predictor variable was needed. For this reason, the mean of the repetitions was used as the datum for those analyses. Similarly, the mean of the two repetitions of the psychophysical procedure was used as the datum for MAWL. All statistical analyses were performed with the SAS/STAT® software system (SAS Institute 1990).

2.4.1. *Correlation analyses*: A Pearson product-moment correlation matrix was calculated that included the nine predictor variables, the dependent variable, height and weight. This analysis partially achieved specific aims 1 and 2.

The three types of testing discussed earlier were isometric, isokinetic and isoinertial. One problem with the correlation matrix mentioned above is the large number of variables. In order to provide a more succinct comparison of the relationship between MAWL and the isometric, isokinetic and isoinertial measurements, a matrix of canonical correlation coefficients was calculated. The goal of canonical correlation analysis is to identify and quantify the associations between two sets of variables (Johnson and Wichern 1988). The variable sets used were MAWL, isometric measures (IMET15, IMET75), isokinetic measures (IKIN0.1, IKIN0.2, IKIN0.4, IKIN0.6, IKIN0.8), and isoinertial measures (XFAC, ISOPOW). To avoid the potential bias of comparing correlations among groups with different numbers of variables, adjusted canonical correlations were used.

2.4.2. *Structural equation model*: The most comprehensive statistical analysis performed was a latent variable structural equation model (LVSEM). LVSEMs are sets of linear equations used to specify 'phenomena' in terms of cause-and-effect relationships (Johnson and Wichern 1988). These analyses are sometimes referred to as path analysis or LISREL models because of the popularity of the LInear Structural RELationships software (Jöreskog and Sörbom 1993). In a general sense, these models do not focus on individual observations such as in analysis of variance, but focus on modelling the covariance structure of the data set (Bollen 1989). To the authors' knowledge, these techniques have not been applied in previous industrial ergonomics research.

Typically, multivariate ordinary least squares (OLS) regression has been used to analyse data sets similar in nature to the one that was collected. However, it was expected that strong multicollinearity would exist between several of the predictor variables. Multicollinearity increases the standard errors of the parameter estimates of the collinear variables, which reduces the statistical certainty of the inferences concerning the parameter estimates. Multicollinearity also poses interpretation problems. The interpretation of regression coefficients measuring the change in the expected value of the dependent variable while all other regressor variables are held constant is not fully applicable (Neter *et al.* 1990). LVSEMs are an alternative to regression and are also a more statistically parsimonious manner of analysing such a data set.

To use an LVSEM, one assumes that there are underlying latent factors that determine (in a regression sense) the values of the observable (or manifest) variables. As an example, for each subject the authors believe that there is a general isokinetic strength factor that, to varying degrees, determines the subject's outcomes IKIN0.1–IKIN0.8. Similarly, the authors postulate the existence of latent isometric strength and isoinertial capacity factors. The primary model then uses MAWL as the response variable, and the three latent factors as predictors. The benefits of this approach over ordinary regression are: (1) the primary predictor variable set has been reduced from nine variables to three variables, and (2) the model explicitly represents the effects of these 'overall' measures, while retaining all information from the individual measures.

The initial form of the structural relationships is shown in figure 3. The straight arrows in figure 3 indicate causal relationships and the double-headed curved lines represent correlations. The latent variables are indicated by circles and the manifest variables are indicated by rectangles. The error terms, δ_i and ε, represent error terms for predictor and response variables, respectively. The ϕ_i terms are correlations between latent variables. These correlations provide a means of accounting for some of the multicollinearity discussed earlier. Correlations between the observed predictors (variables in rectangles on left side of figure 3) are functions of these ϕ_i, the nine path coefficients on the left side of figure 3, and the δ_i.

2.4.3. *Miscellaneous analyses*: In addition to the analyses above, a t-test was used to test whether or not there was a statistically significant difference between IMET15 and IMET75. Owing to the correlation between the two measures, a paired t-test was used.

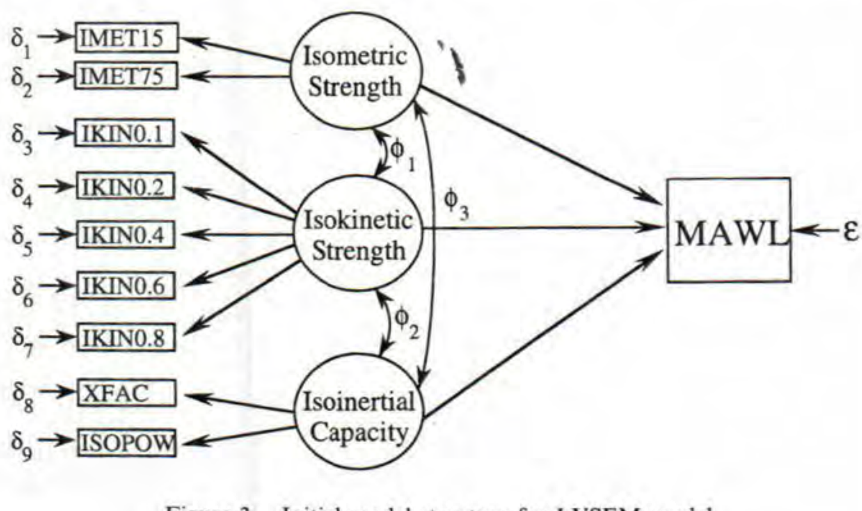

Figure 3. Initial model structure for LVSEM model.

The five isokinetic measurements provided mean peak power and mean peak force values at each velocity. Repeated-measures analysis of variance (ANOVA) was used to test the effect of velocity on force and power. Velocity versus power and velocity versus force curves, with standard error bars, were generated. Currently, there are no such curves for composite lifting measurements.

The three force and power measurements at each of the five velocities for each subject were not averaged for the ANOVAs to permit a more efficient use of the data. The analyses were treated as single-factor repeated measures ANOVAs with subsampling. The denominators for the *F*-tests were in accordance with the procedures described by Neter *et al.* (1990).

3. Results

3.1. *Summary statistics*

Table 2 presents summary statistics for each variable measured. The means, standard deviations, and extreme values of each variable are shown.

Table 3 presents MAWL values that accommodate 10, 25, 50, 75 and 95% of the male population for a frequency of one lift per 8 h. The values for the present study, Ciriello and Snook (1978), and Ciriello and Snook (1983) are based upon the assumption that the MAWL values follow a normal distribution, and that the sample is representative of the population. The normality assumption was used by Snook (1978) and Snook and Ciriello (1991). The values from Snook and Ciriello (1991) are based upon the Ciriello and Snook (1983) data; however, Snook and Ciriello (1991) adjusted the mean value based on a larger sample of workers performing a floor to 51 cm lift. The values of Snook (1978) are based upon the values of Ciriello and Snook (1978), and it appears that the data were adjusted in the same manner.

3.2. *Correlation analyses*

Table 4 presents the Pearson product-moment correlations between all pairs of variables measured. The *p*-values provided under each coefficient are for testing the hypothesis that $\rho_{ij} = 0$, where ρ_{ij} is the correlation between the *i*th and *j*th variables, versus the alternative that $\rho_{ij} \neq 0$. The correlation coefficients indicate the strengths of the linear associations between pairs of variables. A graphical examination of the relationships between MAWL and the predictor variables indicated that the relationships are indeed linear.

Table 2. Summary statistics for dependent and predictor measures.

Variable	Mean	SD	Minimum	Maximum
IMET15 (N)	802.87	190.45	524.60	1262.90
IMET75 (N)	990.29	198.42	612.84	1339.09
IKIN0.1 (N)	885.92	194.41	516.55	1323.97
IKIN0.2 (N)	843.66	201.30	526.49	1190.59
IKIN0.4 (N)	776.06	183.61	473.98	1033.07
IKIN0.6 (N)	723.24	183.68	393.10	1048.68
IKIN0.8 (N)	686.93	199.49	383.17	1027.40
XFAC (kg)	55.79	12.14	34.02	83.91
ISOPOW (W)	1210.89	256.18	857.55	1962.97
MAWL (kg)	56.06	13.71	36.34	92.08

Table 3. Comparison of male MAWL values (kg) for a frequency of 1 lift per 8 h from several studies

Study	Percentage of population accommodated				
	10	25	50	75	90
Ciriello and Snook (1978) ($n=15$)*†	88	75	60	45	32
Snook (1978)‡	64	55	46	37	29
Ciriello and Snook (1983) ($n=10$)*§	82	72	61	50	40
Snook and Ciriello (1991)¶	65	55	44	33	23
Present ($n=25$)*"	74	65	56	47	38

* Assuming a normal distribution.

† Floor to knuckle, box width (distance in sagittal plane) = 36 cm, box length (distance between hands) = 57 cm.

‡ Floor to 76 cm, box width = 36 cm.

§ Floor to 51 cm, box width = 36 cm, box length = 57 cm.

¶ Floor to 76 cm, box width = 36 cm, box length = 57 cm.

" Floor to 76 cm, box width = 30.5 cm, box length = 30.5 cm.

Table 4. Correlation matrix for dependent and predictor variables (significance levels are below the correlation coefficients).

Variable	IMET75	IKIN0.1	IKIN0.2	IKIN0.4	IKIN0.6	IKIN0.8	XFAC	ISOPOW	MAWL
IMET15	0.71382	0.60812	0.50662	0.59196	0.46218	0.54313	0.33461	0.59461	0.62622
	0.0001	0.0013	0.0098	0.0018	0.0200	0.0050	0.1021	0.0017	0.0008
IMET75		0.72476	0.68252	0.76396	0.69808	0.63881	0.52808	0.67053	0.61574
		0.0001	0.0002	0.0001	0.0001	0.0006	0.0067	0.0002	0.0011
IKIN0.1			0.90744	0.86148	0.76247	0.74840	0.61657	0.76310	0.79042
			0.0001	0.0001	0.0001	0.0001	0.0010	0.0001	0.0001
IKIN0.2				0.92460	0.81146	0.80355	0.61278	0.65296	0.62677
				0.0001	0.0001	0.0001	0.0011	0.0004	0.0008
IKIN0.4					0.87255	0.83694	0.62897	0.68707	0.65531
					0.0001	0.0001	0.0008	0.0001	0.0004
IKIN0.6						0.88070	0.60471	0.72709	0.67281
						0.0001	0.0014	0.0001	0.0002
IKIN0.8							0.55132	0.81652	0.73549
							0.0043	0.0001	0.0001
XFAC								0.61151	0.49835
								0.0012	0.0112
ISOPOW									0.83849
									0.0001

Correlations between height and weight and the strength measures were also examined. Height was not significantly correlated with any of the strength measures. Weight was significantly correlated, albeit weakly, with IKIN0.8 ($r = 0.4078$, $p = 0.0430$) and with XFAC($r = 0.5065$, $p = 0.0098$). An interesting trend in the correlations between weight and the isokinetic strength measures was that the correlations increased in an approximately linear fashion from 0.1689 at a velocity of 0.1 m s^{-1} to 0.4078 at a velocity of 0.8 m s^{-1}. It is possible that the inertia of the upper body enhances isokinetic force capabilities as velocity increases.

Table 5 gives the adjusted canonical correlation matrix for the sets of isometric (IMET15, IMET75), isokinetic (IKIN0.1, IKIN0.2, IKIN0.4, IKIN0.6, IKIN0.8), and isoinertial variables (XFAC, ISOPOW), and MAWL. The *p*-values shown under each coefficient are for the likelihood ratio test of the hypothesis that the first canonical correlation and all smaller canonical correlations are 0 in the population. Table 5 presents the first canonical correlation, which is the correlation between the pair of linear combinations of the two sets of variables having the largest correlation.

3.3. *LVSEM results*

The LVSEM results are presented in the form of the path diagram shown in figure 4. The path coefficients are in standardized form to permit a direct comparison of the coefficients. The values in parentheses under the estimated path coefficients for the paths leading from the latent variables to MAWL are the standard errors of the estimated path coefficients.

Table 5. Adjusted canonical correlation coefficients (significance levels are below the correlation coefficients).

Variable	Isokinetic	Isoinertial	MAWL
Isometric	0.7629	0.6730	0.6616
	0.0046	0.0037	0.0014
Isokinetic		0.8770	0.8756
		0.0001	0.0001
Isoinertial			0.8365
			0.0001

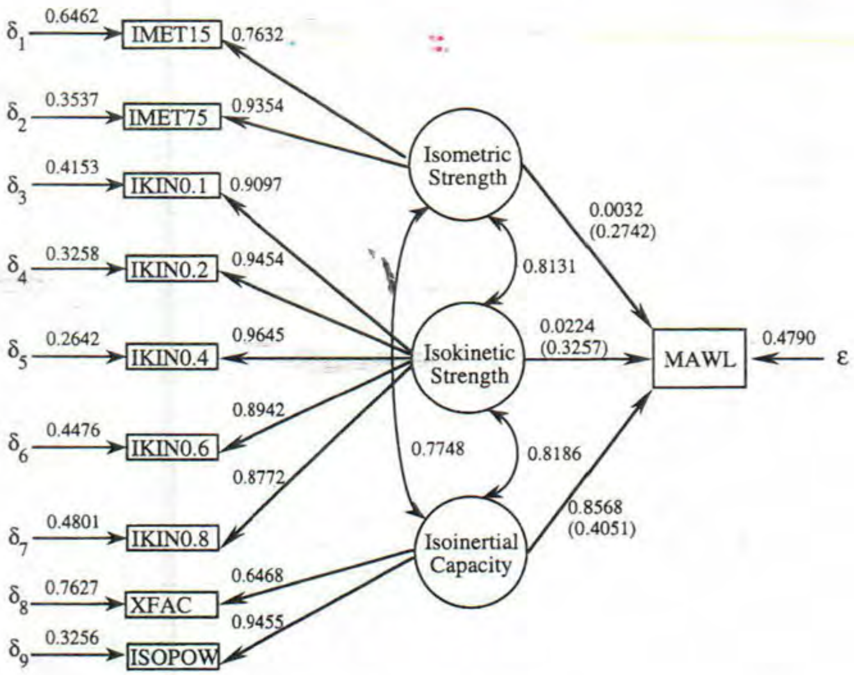

Figure 4. LVSEM results.

3.4. *Miscellaneous analyses*

A *t*-test was used to test the hypothesis that the difference between the isometric variables (IMET75 − IMET15) is equal to zero. This hypothesis was rejected ($p < 0.0001$), indicating that the mean of IMET75 is significantly greater than the mean of IMET15.

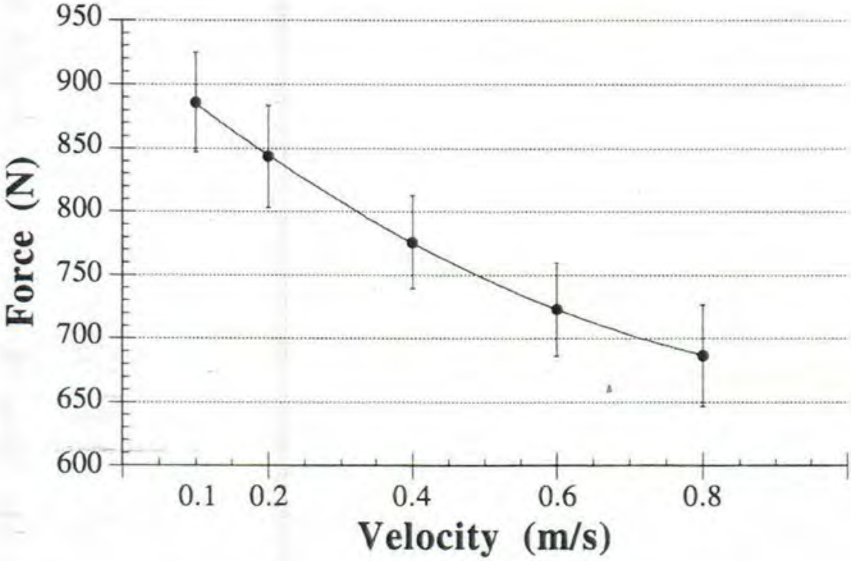

Figure 5. Effect of velocity on maximal isokinetic lifting strength (error bars represent the standard errors of the means).

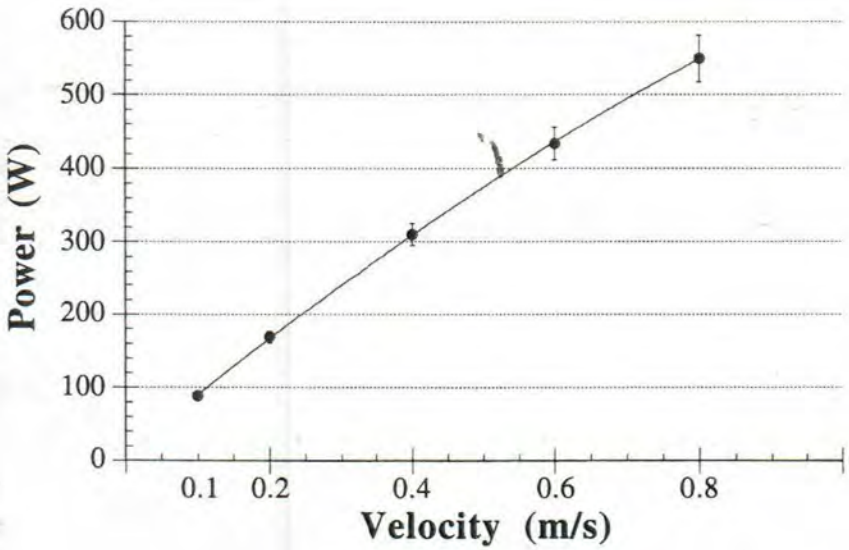

Figure 6. Effect of velocity on maximal isokinetic lifting power (error bars represent the standard errors of the means).

Figures 5 and 6 illustrate the means and standard errors of the means for isokinetic strength and isokinetic power, respectively, as a function of velocity. Figure 5 shows that composite lifting strength decreases as velocity of movement increases, as was expected. Power increases as velocity increases over the range of velocity studied.

The results from the ANOVA analyses for force and power as the dependent measures indicate that isokinetic force and power capabilities are significantly affected by velocity ($p < 0.0001$). For the model with force as a dependent variable, Duncan's Multiple Range Test indicated that the mean force at 0.1 m s^{-1} was not significantly different from the mean force at 0.2 m s^{-1}, and that the mean force at 0.6 m s^{-1} was not significantly different from the mean force at 0.8 m s^{-1}. For the model with power as a dependent variable, the mean power values at each velocity were significantly different from the mean power values at the other velocities.

4. Discussion

The mean IMET75 value (990.3 N) was 123% of the mean IMET15 value (802.9 N). Rühmann and Schmidtke (1989) measured the isometric strength of 873 male industrial workers at vertical heights of 15 and 75 cm, as in the present study. For males, the mean value at 15 cm was approximately 900 N and the mean value at 75 cm was approximately 1200 N (the results of the study were presented graphically). Kumar and Chaffin (1987) reported a mean value of approximately 900 N for a test similar to IMET15, with the exception that Kumar and Chaffin used a vertical height of 5 cm.

For the present study, the mean IMET15 value was approximately 100 N lower than Rühmann and Schmidtke's (1989) value, while the mean IMET75 value was approximately 200 N lower. This is somewhat surprising given that Rühmann and Schmidtke (1989) used subjects up to 65 years of age. However, the current study used the mean maximum strength over a period of 3 s, whereas Rühmann and Schmidtke (1989) used what the authors believe, based on the information provided in the manuscript, is closer to a peak value. Given the differences in procedures, apparatus, and subjects, the values are reasonably close.

In addition to isometric strength, Kumar and Chaffin (1987) measured isokinetic strength at velocities of 0.2 and 0.6 m s^{-1}. For the present study, the mean IKIN0.2 value was 843.66 N, compared to the value of slightly less than 800 N reported by Kumar and Chaffin (1987). The mean IKIN0.6 value was 723.23 N, compared to the value of slightly more than 700 N reported by Kumar and Chaffin (1987). The values from the two studies compare quite well.

Table 3 provided a comparison of the MAWL values from the present study to the unadjusted databases developed by the Liberty Mutual Insurance Company (Ciriello and Snook 1978, 1983). This comparison reveals that the mean MAWL value from the present study is 4–5 kg, or about 7–9%, lower than the values generated at Liberty Mutual using industrial subjects of a wider age range. This is consistent with the results of Mital (1987), who compared MAWL values from 74 students with data collected from 74 experienced industrial material handlers. On average, male student subjects selected MAWL values 11% less than the industrial handlers.

The mean XFAC value compares well with previous studies. The mean value of 55.79 kg was similar to the mean values of 54.25 kg reported by Ayoub *et al.* (1982), 60.05 kg reported by Jiang *et al.* (1986), and 50.0 kg reported by Ayoub *et al.* (1987).

4.1. *Correlation analyses*

The correlation matrix in table 4 provides results that help to achieve specific aims 1 and 2. The goal of the first specific aim was to determine if power is related to lifting capacity. The correlation between ISOPOW and MAWL (0.8385) and the significance of the coefficient ($p<0.0001$) indicate that power as measured in this study is related to MAWL for a frequency of one lift per 8 h.

The correlations between MAWL and the predictor variables help to achieve the second specific aim, which was to compare the relationships between MAWL and power and between MAWL and previously used predictors of lifting capacity. Table 4 indicates that ISOPOW was the measure most strongly related to MAWL, followed by IKIN0.1.

The correlations between MAWL and the isometric variables were of similar magnitudes, and were lower than the correlations between MAWL and all dynamic variables except XFAC. The correlation between XFAC and MAWL was the lowest (0.4984). However, one observation (MAWL = 48.9 kg, XFAC = 83.9 kg) lowered this correlation considerably. Without this point, the correlation between MAWL and XFAC is 0.6324 ($p<0.0004$), which is about equal to the correlations between MAWL and IMET15 and between MAWL and IMET75.

One reason for the low correlation between MAWL and XFAC, relative to the correlations between MAWL and the other dynamic predictor variables, may be that the precision of the incremental lifting test is limited to 4.5 kg. Additionally, this test requires greater upper-body strength than lifting from the floor to knuckle height. Failure on the XFAC test usually occurs at approximately waist height or higher. MAWL was assessed for a range of 0 to 76 cm, versus the 0 to 183 cm range used for the XFAC test.

The relationships between MAWL and the isokinetic measures increase as velocity increases with the exception of the correlation between MAWL and IKIN0.1, which was the highest. There is no theoretical explanation for this finding. One potential factor is simply sampling variability, i.e. this finding may be sample specific. Further research will determine if this finding is consistent.

The correlations between the isokinetic strength measures indicate that the closer the velocity of two tests, the higher the correlation will be. However, correlations between all of the isokinetic strengths were fairly high. The correlations between the isometric and isokinetic variables were between 0.5066 and 0.7640, with no consistent pattern with respect to velocity.

The canonical correlation coefficients indicated that the isometric measures were most strongly related to the isokinetic measures. The relationships between the isometric measures and the isoinertial measures and between the isometric measures and MAWL were nearly equal. The reason for this pattern is likely because the isokinetic measures have the restriction that velocity be held constant, whereas the isoinertial measures have no restriction on velocity. With respect to velocity, the isometric and isokinetic measures are more similar than the isometric and isoinertial measures. The relationships between the isokinetic measures and the isoinertial measures and between the isokinetic measures and MAWL differed very little.

The isokinetic measures were more strongly related to MAWL than were the isoinertial measures. One reason for this may be the poor correlation between MAWL and XFAC (0.4984), as XFAC is one of the isoinertial measures. All of the isokinetic measures were more strongly correlated with MAWL than was XFAC.

The canonical correlation between the isoinertial measures and MAWL (0.8365) was considerably higher than the canonical correlation between the isometric measures and MAWL (0.6616).

4.2. *LVSEM*

The results of the LVSEM model presented in figure 4 provide further support for the results discussed earlier. The correlations between the latent variables are similar in magnitude to the respective canonical correlations that were presented in table 5. These correlations also indicate the strong multicollinearity between the predictor variables on the left side of figure 4.

The fairly large error effect (0.7627, meaning 76.27% of the variance is unexplained) for XFAC on the left side of figure 4, and the lowest path coefficient among the predictor variables for XFAC (0.6468) suggest that XFAC is not strongly related to the underlying isoinertial capacity variable. This suggests that XFAC is a relatively poor predictor of MAWL, although this inference is indirect since the model does not explicitly represent MAWL in terms of XFAC. The second highest path coefficient for the predictor variables was for ISOPOW (0.9455), which further supports the findings that ISOPOW is strongly related to MAWL, as discussed earlier.

The error terms and the path coefficients for the isometric variables suggest that IMET75 was a stronger predictor than IMET15. The Pearson correlations between IMET15 and MAWL (0.62622) and IMET75 and MAWL (0.61574) were approximately equal; however, the LVSEM is a multivariate analysis. IMET75 was more strongly correlated with the dynamic predictor variables than was IMET15. In the multivariate analysis, IMET75 is a better predictor.

The most important path coefficients are those leading from the latent variables to MAWL. Unfortunately, as figure 4 shows, the standard errors of the estimated path coefficients are relatively large. There are several potential reasons for the high variability of these estimates. The first is that the sample size of 25 is low relative to the number of parameters estimated. Second, the high multicollinearity among the predictors, indicated by the high correlations among the latent variables, reduces the precision of the estimates. Although the *a priori* expectation concerning multicollinearity among predictors was that the correlations would be high, the authors did not expect such high multicollinearity among all predictors. Nevertheless, the problem of multicollinearity in the LVSEM is less than would have been in a full ordinary least-squares regression model with nine highly correlated predictors, rather than just three.

The practical implications of the high standard errors of the path coefficients are that the path coefficients should not be interpreted in an absolute sense. The analyses presented earlier indicate that ISOPOW was the best predictor of MAWL, and this explains why the isoinertial capacity path coefficient estimate is high. Based on the correlation results, it would seem likely that the near zero coefficients leading from isometric strength and isokinetic strength should be somewhat higher. However, like regression analysis, the LVSEM analysis assesses the influence of each predictor variable with the others held constant. Correlation methods do not isolate individual effects in this fashion; therefore, the regression coefficients and correlation coefficients measure distinct quantities. The regression estimates are more reasonable, since the authors wanted to assess the unique contributions of those individual predictors, and not effects confounded with the effects of other variables.

4.3. *Implications for industrial screening programmes*

Overall, the results indicate that dynamic measures, with the exception of XFAC, are superior to isometric strength for use in assessing the capacity to perform a floor to knuckle lift for a frequency of once per 8 h shift. Additionally, ISOPOW was superior to all measures.

4.4. *Limitations of the results*

The primary limitation of the study is that the relationships between determinants of lifting capacity and MAWL were only established for MAWL for a frequency of one lift per 8 h and one range of lifting. Likewise, only one size box was used. The correlations between the predictor variables and MAWL cannot be assumed to hold for all variations of lifting tasks. It is expected that similar results would be found for lifting tasks with low frequencies. At higher frequencies, the capacity of the cardiovascular system becomes the limiting factor, rather than the strength capacity of the musculoskeletal system. It would therefore be expected that the correlations between the various capacity measures investigated here and MAWL would decrease as frequency increases. Ciriello and Snook (1978) found such a pattern among correlations between isometric strength and MAWL. For tasks with intermediate frequencies it is likely that accurate prediction of MAWL would require the use of both strength and aerobic capacity measures.

A secondary limitation of the study is that the subject population was comprised of male subjects, most of whom were college students. The study should be replicated using female subjects. Adjustments would need to be made to the ISOPOW test to reflect the lower XFAC capacity of females relative to males. Additionally, the oldest subject was 26 years old, thus the applicability of the results to an occupational population should be examined. Therefore, it would be prudent to replicate the study using an industrial population of male and female subjects.

The final limitation of the study is that isoinertial power was only measured using one mass. Any conclusions regarding the relationship between power and MAWL need to be restricted to conclusions concerning the conditions investigated in this study. It is unlikely that the correlations between MAWL and isoinertial power would be the same for isoinertial measurements using different masses.

5. Conclusions

The results of this study further support the literature which indicates that dynamic strength is superior to isometric strength for predicting lifting capacity. With the exception of the 6 ft incremental lift test, all the dynamic measures were more strongly related to MAWL than were the isometric measures. The potential reasons for the poor association between MAWL and XFAC were discussed earlier.

Although the manner in which maximal lifting power was measured was limited to one condition (ISOPOW), the results indicate that power is indeed related to the ability to lift a load from the floor to a shelf at 76 cm. Given the convincing role of power in predicting performance of various athletic events, and the empirical results of the present study, the role of power in predicting lifting capacity should be explored further.

In the future, a study should be conducted to investigate the relationship between the predictor variables investigated here and a wider range of dependent measure conditions. Particularly, the relationships between the predictor variables and MAWL for a wider range of frequencies should be examined. At higher frequencies, it is likely that aerobic capacity is a more important determinant of lifting capacity than the strength and power measures investigated in the current study. Similarly, ranges of lift other than floor to knuckle should be examined. For a knuckle to shoulder lift, the vertical range of the various tests would need to be adjusted so that they would be representative of the actual lifting tasks.

Since power was assessed using only one technique and load, future research should also investigate how varying the load affects the relationship between MAWL and power. For the present study, the ISOPOW test was only conducted using a 25 kg load due to concerns about the safety of using heavier loads for this test.

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