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Measurement and prediction of single and multi-digit finger strength

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Hand and finger strength has direct application in the design of human-machine interfaces involving the whole hand or single digits. Limited finger strength data is available, however, particularly for practical situations such as pinching and poking. A study was conducted in which strength in a variety of couplings was collected from 100 participants, in order to enhance and supplement the existing literature. Differences between couplings, gender, and age groups were evaluated. Strength was significantly higher for multi-digit couplings as compared with single digit couplings ($p < 0.05$). In addition, female strength was approximately 70% of male strength across all couplings. No significant differences were found between three age groups ranging from 18 to 40 + years old. Multiple regression models were used to determine whether finger strength could be predicted from other strength measures and anthropometry. Regression results suggest that finger strength can be predicted with only moderate accuracy using these variables (R^2-adj: 0.45–0.64; standard error: 12–19 N). Such models are easy to implement, however, and begin to overcome the limitations of direct finger strength measurements.

1. Introduction

Consideration of hand and finger strength is essential during industrial design of hand intensive tasks to minimize discomfort and the risk of upper extremity injuries and their associated costs. Occupational risk factors for upper extremity musculoskeletal disorders (MSDs) include repetitive and forceful exertions, mechanical stresses, extreme postures, vibration and low temperature (Armstrong 1986, Bernard 1997, Viikari-Juntura and Silverstein 1999). Many hand intensive tasks require extreme levels of force exertion, often in combination with non-neutral hand and wrist postures (Armstrong 1986, Palanisami *et al.* 1994, Bernard 1997, Fredriksson *et al.* 1999). Safe force levels for hand intensive work have yet to be determined. Instead, measures of capacity (e.g. strength) are often provided as a basis for comparison to task demands during design and evaluation (Peebles and Norris 2003).

Extensive past research has focused on whole-hand grip strength and the effects of variables such as gender and handle width. There have also been a few reports of hand strength in couplings with handles and levers. Relatively few investigations, however, have specifically addressed finger strength, particularly in practical

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situations such as pinching and poking. The most extensive data on hand and finger strength have been reported by Swanson *et al.* (1970), Mathiowetz *et al.* (1985), Imrhan (1989), Chao *et al.* (1989) and Crosby *et al.* (1994).

Acquisition of strength measures in general, and finger strength in particular, can require specialized equipment that is not easily integrated into a working environment. A practical question thus arises as to whether force capability in specific finger couplings can be *predicted* from other more accessible measures, thereby allowing the practitioner to estimate strength. Accessible or easily obtainable measures are considered here as those that can be determined using simple measuring devices or commercial gauges.

Past research regarding the prediction of hand strength has been limited to grip and multi-digit pinches. Rice *et al.* (1998) predicted grip strength from various anthropometric and strength measures and found that forearm circumference was a moderately accurate predictor ($R^2 = 0.80$). Hallbeck *et al.* (1989) used regression to predict pinch strength from hand anthropometric measures and reported somewhat less accurate predictions ($R^2 = 0.40-0.59$). Eksioglu *et al.* (1996) compared regression techniques with artificial neural networks to predict pinch strength, using numerous anthropometric and physiological measures as predictor variables, and found that artificial neural networks provided more accurate predictions. Despite these indications, there have been no thorough investigations specifically addressing the prediction of finger strength in a range of single and multi-digit couplings.

Due to the relative scarcity of maximum finger forces (strength), strength measures obtained in the study described here were compiled for several single and multi-digit couplings. These data were intended to both supplement existing reports, and also provide new results regarding index finger strength in several couplings. Given earlier evidence of age and gender effects on strength (Mathiowetz *et al.* 1985, Viitasalo *et al.* 1985, Imrhan 1989, Hallbeck 1994), it was hypothesized that similar differences in finger strength would exist across several different hand couplings. A second experimental goal was to determine the inter-correlations within and among finger strengths, simple grip strength, and anthropometry, and to evaluate whether finger strength could be estimated from other measures, particularly single digit strength which has yet to be investigated.

2. Methods

2.1. *Hand couplings*

Participants performed maximum voluntary exertions of the hand and fingers in seven different hand couplings. The couplings differed in the number of fingers that were used and the positioning of the fingers. Participants were encouraged to relax fingers not required for the exertion, to minimize their contributions to force generation. Specific couplings were chosen to reproduce exertions that are common during hand intensive occupational tasks. For example, pushing buttons, sliding levers, and inserting fasteners all require single or multi-digit couplings similar to those investigated. Each of the seven couplings is described below.

1. *Poke* (index finger): The palm faced down with the index finger in line with the forearm. Force was exerted at the tip of the index finger, such that the fingernail did not interfere with the force exertion, and the force was in line with the finger and forearm.

2 *90° Distal Pad Pull* (index finger): The palm faced down. Force was exerted at the pad of the index finger while the middle phalangeal joint was bent at approximately a 90° angle. The finger 'hooked' the force gauge.
3 *180° Distal Pad Press* (index finger): The palm faced down with the index finger in line with the forearm and held horizontally. A downward force was exerted at the pad of the index finger.
4 *Lateral Pinch*: The palm faced medially. Force was exerted between the pad of the thumb and the opposing lateral side of the middle phalanx of the index finger, through the opposing surfaces. Remaining fingers were bent and held together to support the index finger (see figure 1c in Imrhan 1989).
5 *Palmar Pinch*: The palm faced down. Force was exerted between the pad of the index finger and the pad of the thumb, through the centres of the opposing pads (see figure 1a in Imrhan 1989).
6 *Three-jaw Chuck Pinch*: The palm faced down. Force was exerted between the pads of the index and middle fingers together and the pad of the thumb, through the centres of the opposing pads (see figure 1b in Imrhan 1989).
7 *Power Grasp*: The palm faced inward, toward the body. The total inner hand surface grasped a dynamometer handle that ran parallel to the knuckles. The dynamometer faced away from the participant, such that the participant could not read the gauge (see figure 1 in Mathiowetz *et al.* 1985).

2.2. *Anthropometric measures*

Nine anthropometric measures were obtained from each participant: body mass (no shoes), stature, hand length, hand breadth, wrist breadth, wrist circumference, forearm circumference (fist relaxed), forearm circumference (fist flexed), and forearm-hand length. Values were recorded as part of the participant data, to the nearest millimetre, and used for subsequent generation of predictive models. Descriptions of each measure were adapted from the Anthropometric Source Book Volume II: A Handbook of Anthropometric Data (Webb Associates 1978). Participant's stature and body mass were measured using a beam scale with built-in height pillar. The remaining anthropometric measures were measured using an anthropometer and metric tape measure.

2.3. *Participants*

The 100 participants (50 men and 50 women) were university students or residents of the surrounding community. Each completed an informed consent procedure approved by the Virginia Polytechnic Institute and State University IRB. Participants ranged in age, from 18 to 65 years, and were intended to represent a typical distribution of industrial employees. Three age groups were created for subsequent determination of age effects: 18–29 years, 30–39 years, and 40+ years. All participants reported good health and no history of upper limb pain or musculoskeletal injuries within the prior 6 months.

2.4. *Force measurement*

The experimental environment simulated seated work. An adjustable chair was used, with seat height and armrest heights altered as necessary to accommodate each participant. Consistent use of the same chair and table (height at 66 cm) allowed for standardization of postures between participants.

A strain gauge transducer was used to monitor forces exerted by the finger(s), whereas simple grip efforts were performed using a hand dynamometer (Jamar Model 1A), and the force recorded from the analog display. The finger force gauge consisted of two identical aluminum bars held together at their bases, and resembled commercial pinch devices. Wiring between the gauge and amplifier (SC-2043-SG, National Instruments) accommodated either a half or full Wheatstone Bridge arrangement, for loads applied to one or both bars, respectively. Both the half and full bridge arrangements were found to be linear over a 0 – 100 N range with a standard error of 5.5% and 1.8%, respectively. Each configuration was calibrated prior to experimental trials. Raw voltages from the strain gauge system were A/D converted and sampled at 1024 Hz, then low pass filtered (2nd order Butterworth, 10 Hz cutoff) and converted to units of force (N) using custom software.

2.5. *Experimental procedures*

All exertions were performed using the participant's dominant hand while seated. Participants were instructed to maintain a standard position for grip and finger strength measurements. This position, from Fess and Moran (1981), required an upright posture with the feet on the floor, shoulder adducted, elbow flexed at 90°, and forearm and wrist in a neutral position. An upright posture was maintained throughout the exertions to control shoulder movement and variations in positioning. The chair supported the nondominant arm to allow the participant to focus all efforts on maximizing the force produced.

Participants were not asked to sustain a maximum force exertion, as is commonly recommended (Caldwell *et al.* 1974), but only to provide a brief peak exertion. This alternate procedure was intended to duplicate many industrial hand-intensive tasks, which typically require a brief maximum or short burst of force (e.g. inserting a fastener). Participants were specifically instructed to ramp up to their peak capacity, sustain the effort for a brief time, and then gradually ramp down, each phase taking approximately 1 s. Unacceptable trials due to inadequate ramping components or lack of a distinct peak force were repeated. An additional *a priori* trial acceptance criterion was specified: forces could not vary more than 15% within a 0.25 s window centered on the overall maximum value. Immediate feedback on a computer display allowed for identification of acceptable data, or indication that the trial had to be repeated. A demonstration of each coupling was provided, as was practice at submaximal levels until participants felt they were familiarized with the task. In general, one or two practice trials were sufficient for each coupling.

Participants performed three trials in each of the seven couplings for a total of 21 trials. To prevent any confounding influences related to ordering (e.g. learning), conditions were presented in a totally randomized order. A minimum of 2 min was provided between each trial, and participants were encouraged to request more rest if any symptoms of fatigue were felt at any point during the experiment.

Dependent measures (peak forces) were determined from the data within a 0.25 s window centred on the overall maximum value. Within this window, the mean value was treated as the 'peak' force and recorded for each trial. The largest peak force from the three repetitions of each coupling was taken as the overall peak force or strength.

2.6. *Statistical analysis methods*

Inspection of the data and goodness of fit tests for both normal (Shapiro-Wilk) and lognormal distributions (Kolmogrow-Smirnow-Lilliefors Test) indicated better fits for the lognormal distribution. P-values ranged from 0.01–0.35 for the normal distribution, and > 0.15 for the lognormal distribution. Therefore, subsequent statistical tests for gender and age effects were performed on log transforms of the strength data. For ease of application, however, distributions for the overall data are presented below as normal. Distributions within gender were not found to be lognormal, therefore, results within gender are also given as normal. A Wilk's Lambda multivariate analysis of variance (MANOVA) was performed to evaluate any gender, age, or interaction effects on the set of dependent variables (single and multi-digit coupling strengths). Subsequently, 2×3 repeated measures univariate analyses of variance (ANOVA) were performed for each dependent variable. Pearson Correlation Coefficients (r) were used to examine the relationships within and among the strength and anthropometric measures. All statistical tests were considered significant when $p < 0.05$.

Several multiple linear regression models were developed, separately for strength in each coupling, and using several sets of predictor variables. Models with minimal subsets of predictor variables were of particular interest. Multiple linear regression was used first, to generate baseline models containing all of the independent variables as predictor variables. Standard stepwise regression techniques (Neter *et al.* 1996) were then implemented using a probability of 0.25 to determine whether a variable should enter or leave the model. Potential predictor variables included grip strength, age, gender, the nine anthropometric measures, and significant two-way interactions among these variables. Additional regression models were developed using multi-digit strengths (palmar pinch, lateral pinch, and three-jaw chuck pinch) as predictor variables for single digit strengths. Simple regression analyses, relating each dependent variable with each independent variable, showed that none of the relationships exhibited any substantial deviation from linearity. As a result, nonlinear terms were excluded.

Alternative modelling approaches were examined for predicting finger strength, including principle components, ridge regression, and model averaging. Principal components analysis was used to create new predictor variables that were orthogonal to each other. Although this type of analysis minimized the effects of multicollinearity (which was substantial as noted in the results below), it did not improve the accuracy of predicted strengths. Ridge regression was considered in an attempt to alter the parameters of the regression models and eliminate negative values (which do not have an obvious physical interpretation). Unfortunately the analysis was only able to shrink the parameters but not change their signs. Model averaging was used to create a composite model based on the three best stepwise regression models (Raftery *et al.* 1997). Lastly, to examine a potential gender difference, models were developed separately for each gender, using multiple linear and stepwise regressions. None of these additional approaches yielded any improvements in predictive ability, and were not pursued further.

Quantitative model evaluations were conducted using linear regression (measured vs. predicted strengths), and the resulting associated adjusted coefficients of determination (R^2-adj) and standard errors. A final set of predictive models was chosen based on these measures of model performance, ease of use, consistency of predictor variables, and face validity of regression parameters. The overall goal was to select a predictive model for each coupling that was statistically significant, accurate, and contained variables that were relatively easy to obtain.

2.7. *Strength prediction*

Independent verification of the selected models was conducted in order to substantiate predictive ability. Each model (one for each coupling) was used to predict the strengths of 15 additional participants (eight men and seven women). Participants ranged in age from 21 to 52 years, and experimental procedures identical to those outlined above were used to obtain strength values. Model evaluations were conducted using linear regression as above (measured vs. predicted strengths).

3. Results

3.1. *Anthropometry*

Mean anthropometric values for males were consistently higher than for females, though their ages were similar (table 1). Variability in hand and forearm measures was relatively consistent between the two genders.

3.2. *Finger strength and factor effects*

Strength was significantly higher for multi-digit couplings as compared with the poke and press single digit couplings, whereas grip strength was considerably higher than all couplings that only involved the digits (table 2). Standard deviations increased proportionally to the mean strength magnitude, with the largest standard deviation being associated with grip. Consistent coefficients of variation (31.76–42.80%) further suggested relatively constant strength variability relative to the mean for all of the measures. There were, however, slightly larger coefficients of variation for some of the couplings, particularly the poke, press, and pull, which involved only one finger.

Considerable differences were found between genders for all seven couplings (table 2). Gender differences were significant both in the multivariate tests and for all univariate tests. Peak forces produced by females were consistently smaller and on the order of 70% of corresponding values for males. Coefficients

Table 1. Summary and gender specific anthropometric characteristics for all participants.

	Total (n = 100)		Male (n = 50)		Female (n = 50)	
Measure	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Age (years)	32.7	10.9	32.2	11.1	33.2	11.4
Stature (cm)	166.7	12.4	173.2	7.0	160.2	13.3
Body mass (kg)	76.3	20.3	77.8	15.5	74.8	24.3
Hand length (cm)	18.0	1.0	18.8	0.7	17.5	0.7
Hand breadth (cm)	8.3	0.6	8.8	0.5	7.8	0.4
Wrist breadth (cm)	5.5	0.5	5.9	0.4	5.1	0.3
Wrist circ. (cm)	16.0	1.4	16.9	1.1	15.1	1.0
Forearm-hand length (cm)	45.8	3.0	47.8	2.5	43.9	2.0
Forearm circ. relaxed (cm)	26.9	2.6	28.3	2.4	25.5	2.0
Forearm circ. flexed (cm)	27.5	2.7	29.0	2.5	26.0	2.2

Table 2. Summary and gender specific strength data obtained in each of the finger couplings and for grip.

	Total ($n = 100$)			Male ($n = 50$)			Female ($n = 50$)		
Coupling	Mean (N)	Std. dev. (N)	Coeff. of var. (%)	Mean (N)	Std. dev. (N)	Coeff. of var. (%)	Mean (N)	Std. dev. (N)	Coeff. of var. (%)
Poke	45.95	17.80	38.70	52.58	18.01	34.25	39.31	14.94	38.00
Press	43.05	18.43	42.80	50.90	18.37	36.08	35.20	14.93	42.42
Pull	60.09	25.24	42.01	70.84	27.16	38.34	49.33	17.71	35.91
Lateral	80.93	28.15	34.79	97.02	27.67	28.52	64.84	17.52	27.02
Chuck	79.75	28.96	36.31	95.37	28.26	39.63	64.13	19.94	31.10
Palmar	54.16	18.84	34.78	62.88	19.20	30.54	45.45	13.90	30.59
Grip	370.67	117.73	31.76	452.44	102.94	22.75	288.91	61.33	21.23

of variation were similar, however, and indicated a consistent variation when adjusting for the different magnitudes between genders. As with the combined data, coefficients of variation were slightly larger for the single digit couplings for both genders.

Age differences were not significant either in the multivariate ($p = 0.5076$) or univariate ($p = 0.2416-0.5649$) tests. Strength tended to be similar or increase slightly in the older groups (table 3). Standard deviations were consistent between age groups, but the coefficients of variation were lowest for the 30–39 year age group. The gender × age interaction was not found to be significant in the multivariate test ($p = 0.0743$) or the univariate tests ($p = 0.1826-0.5962$).

3.3. *Correlations*

Correlations (r) within and between the finger and grip strengths and anthropometric measures were variable, although some consistent patterns were observed. In contrast to the finger strengths, simple grip strength showed relatively higher correlations (0.51–0.74) with the anthropometric measures, excluding body mass. Multi-digit strengths generally were more highly correlated with the hand/wrist anthropometric measures (0.37–0.67) as compared to single digit strengths (0.31–0.52). All correlations were significant except for body mass vs. chuck ($p = 0.0581$) and grip ($p = 0.0540$).

Overall, multi-digit strengths were significantly correlated with single digit strengths (0.66–0.77). Pull strength exhibited the highest correlation with each of the multi-digit strengths (0.73–0.77), whereas, the poke displayed the lowest correlations (0.66–0.69).

3.4. *Regression models for prediction of finger strength*

When using all anthropometric measures and grip strength as predictor variables, R^2-adj values ranged from 0.33–0.58 (figure 1). Values for the single digit strengths were consistently lower than those of the multi-digit strengths. Standard errors ranged from 13.9–19.0 N (figure 1), with the largest values corresponding to the 90° distal pad pull, lateral pinch, and three-jaw chuck pinch.

Table 3. Summary and age specific strength data obtained in each of the finger couplings and for grip.

Age	Measure	Poke	Press	Pull	Lateral	Chuck	Palmar	Grip
18–29	Mean (N)	44.27	41.60	57.57	78.93	77.88	51.95	359.91
(n = 61)	Standard deviation (N)	18.12	18.54	23.77	28.96	28.42	17.76	114.55
$\bar{x}$ = 22.2	Coeff. of variation (%)	40.93	44.58	41.29	36.69	36.49	34.18	31.83
σ = 7.8								
30–39	Mean (N)	48.69	44.35	63.76	85.49	86.06	59.32	449.45
(n = 19)	Standard deviation (N)	16.09	16.89	23.87	27.06	30.02	14.85	104.53
$\bar{x}$ = 34.1	Coeff. of variation (%)	33.04	38.08	37.44	31.65	34.88	25.04	23.26
σ = 2.8								
40 +	Mean (N)	48.46	46.24	64.28	82.69	79.45	56.01	328.64
(n = 20)	Standard deviation (N)	18.40	19.84	30.73	27.40	30.24	24.48	109.51
$\bar{x}$ = 49.1	Coeff. of variation (%)	37.96	42.92	47.80	33.14	38.06	43.70	33.32
σ = 2.8								

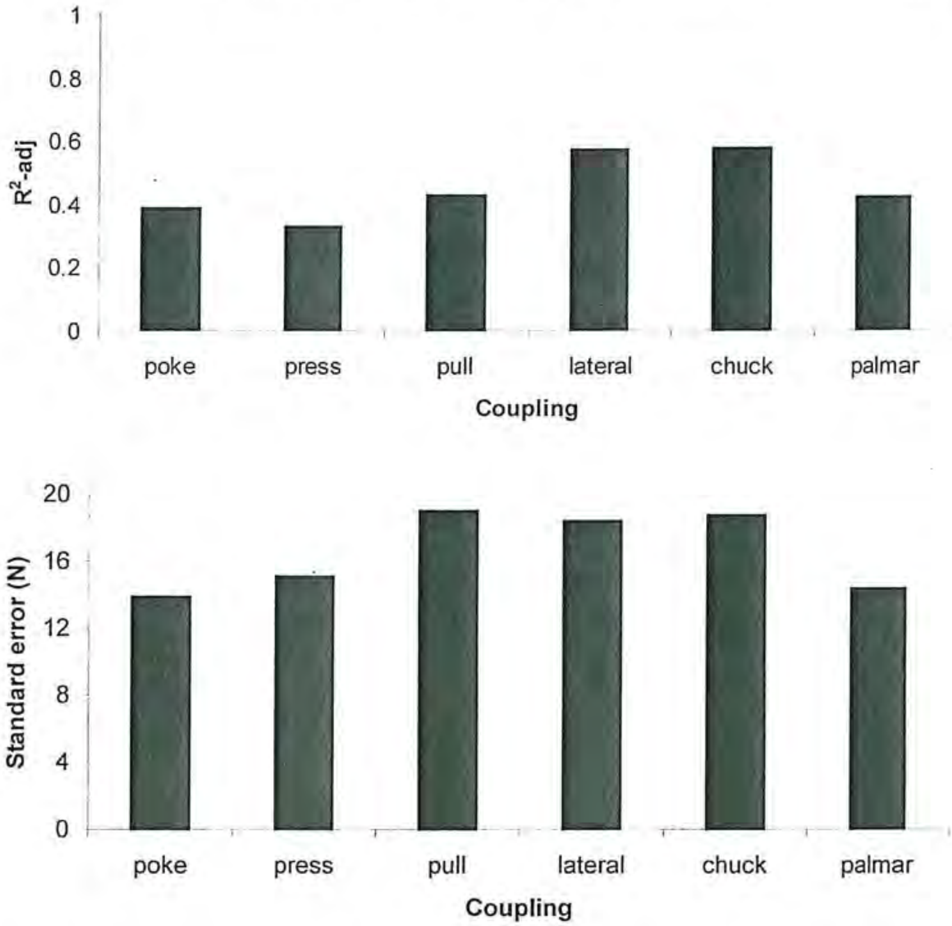


Figure 1. Regression model performance using all anthropometric measures, gender, age and grip strength.

Stepwise regression yielded models with reduced numbers of predictor variables, with specific variables dependent on the coupling. Several patterns did emerge. Grip strength was included in all sets of predictor variables. Hand length was included in each set of predictor variables for the single digit couplings, and both wrist anthropometric measures were excluded. Besides grip strength, the predictor variables for the multi-digit couplings included at least one wrist and one hand measure. R^2-adj values associated with each of the six models ranged from 0.33 to 0.59. Corresponding standard errors ranged from 14.0–19.0 N. Performance of these models was not substantially different from the earlier models that included all predictor variables.

Stepwise regression analysis was repeated using grip, anthropometric measures, and the significant two-way interactions as predictor variables. Better model performance occurred for the multi-digit couplings as compared to the single digit couplings, but was similar to both previous approaches (R^2-adj within 0.01 and standard error within 0.3 N).

When using the pinch strengths as the only predictor variables for single digit strength, R^2-adj values ranged from 0.52 – 0.65 with standard errors of 12.0 – 15.2 N (see figure 2). In addition to pinch strength, grip strength and anthropometric measures were considered as predictor variables. Lastly, significant two-way interactions (between grip and anthropometry) were added to this set of predictor variables. Comparison of model performance (R^2-adj and standard error) showed no substantial differences between models obtained from all three sets of predictor variables (R^2-adj within 0.02 and standard error within 0.4 N).

Using the criteria presented in the Methods, specific models were selected based on model performance, ease of use, and face validity of the regression parameters. These models are presented below for the prediction of single and multi-digit strengths (in Newtons), along with the measures of model performance for each (R^2-adj, standard error).

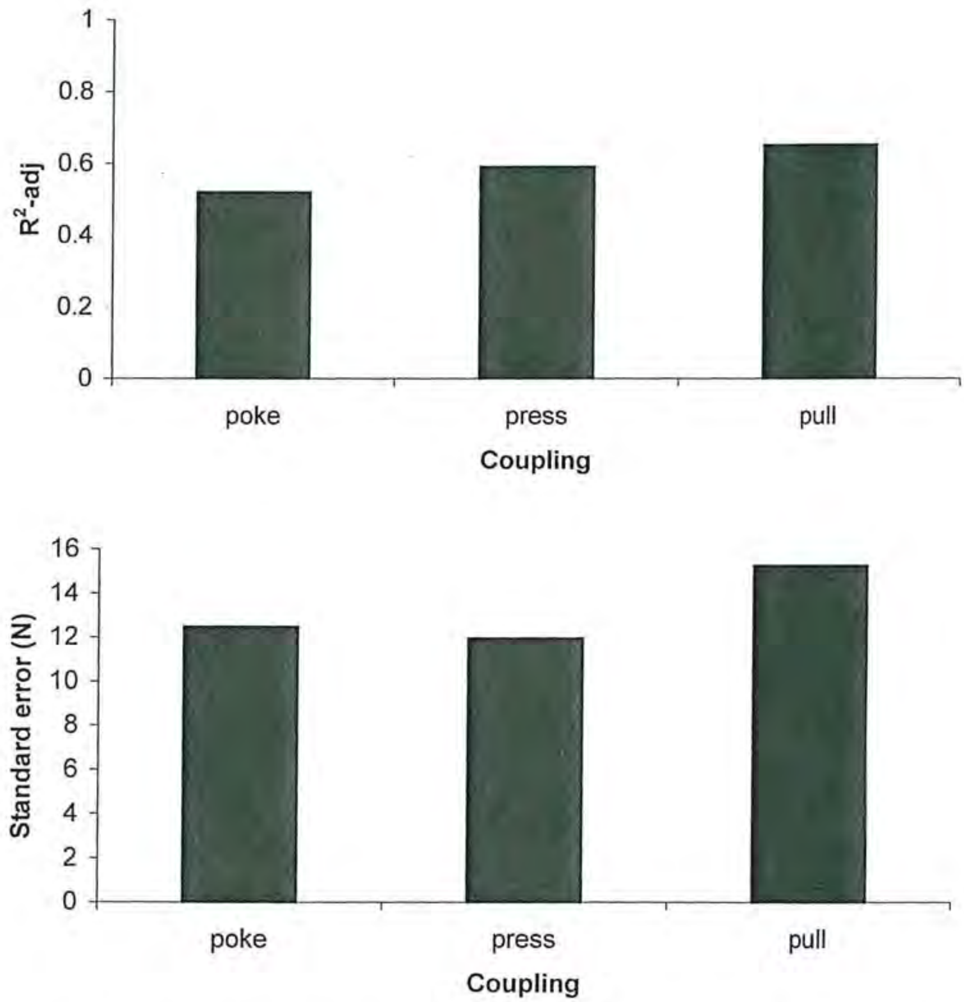


Figure 2. Regression model performance for estimations of single digit strength from pinch strength.

Poke = 6.66 + 0.16LATERAL + 0.10CHUCK + 0.35PALMAR
(R^2-adj = 0.66, SE = 7.02 N)
Press = − 0.21 + 0.20LATERAL + 0.16CHUCK + 0.26PALMAR
(R^2-adj = 0.59, SE = 8.78 N)
Pull = − 1.81 + 0.19LATERAL + 0.20CHUCK = 0.57PALMAR
(R^2-adj = 0.68, SE = 10.77 N)
Lateral = 22.37 + 0.14GRIP − 14.10HL + 19.15WRB + 3.33FHL
(R^2-adj = 0.64, SE = 12.24 N)
Chuck = − 16.93 + 0.17GRIP + 9.67HB − 2.89WRCIRC
(R^2-adj = 0.63, SE = 15.68 N)
Palmar = 39.31 + 0.10GRIP + 0.11BODY MASS − 4.07HL + 7.84WRB
(R^2-adj = 0.53, SE = 9.10 N)

LATERAL:	Lateral pinch strength (N)
CHUCK:	Three-jaw chuck pinch strength (N)
PALMAR:	Palmar pinch strength (N)
GRIP:	Power grasp (Grip) strength (N)
HL:	Hand length (cm)
WRB:	Wrist breadth (cm)
FHL:	Forearm-hand length (cm)
HB:	Hand breadth (cm)
WRCIRC:	Wrist circumference (cm)
BODY MASS:	Lightly clothed body mass (kg)

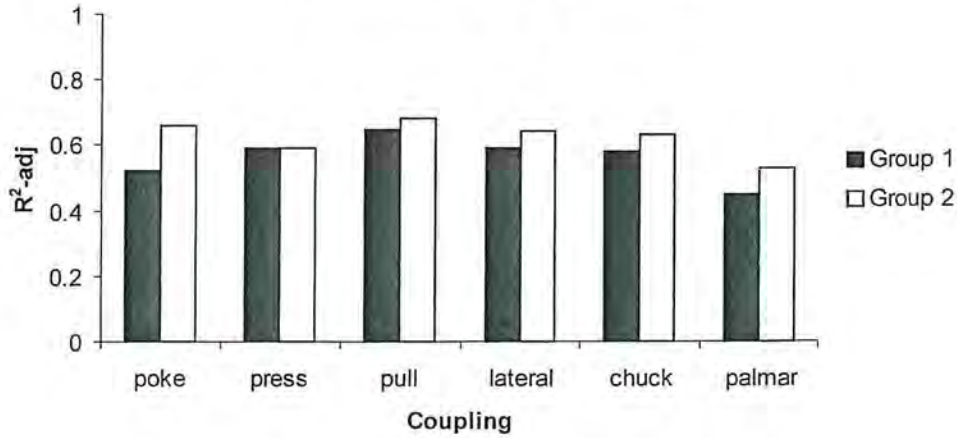
3.5. *Model evaluation*

Independent verification of these selected models, using data from the 15 additional participants, yielded R^2-adj values ranging from 0.53–0.68 (figure 3). The smallest values corresponded to the 180° distal pad press and the palmar pinch. Standard errors ranged from 7.0–15.7 N (figure 3) with the largest values corresponding to the 90° distal pad pull, lateral pinch, and three-jaw chuck pinch.

4. Discussion

Hand intensive tasks and chronic and acute injuries of the upper limbs are common in industry (Armstrong 1996). Improved designs are hampered, however, by incomplete knowledge concerning the strength of the hand and fingers. Many hand intensive industrial tasks replicate one or more of the hand couplings studied here, and the data provided may therefore prove useful for many designs. It should be noted that force magnitude is only one factor of many to consider. For example, information concerning the direction, duration, and frequency of the force exertion must be included during design and evaluation (Caldwell 1970, Goldstein *et al.* 1987).

Prediction of finger strength from easily obtainable measures can potentially provide relevant data without the challenges associated with actual strength measurement. Evaluation of the models developed here implies that such prediction can be achieved, but with only moderate accuracy. In the following discussion, the results are interpreted in more detail, and several limitations and applications are presented.



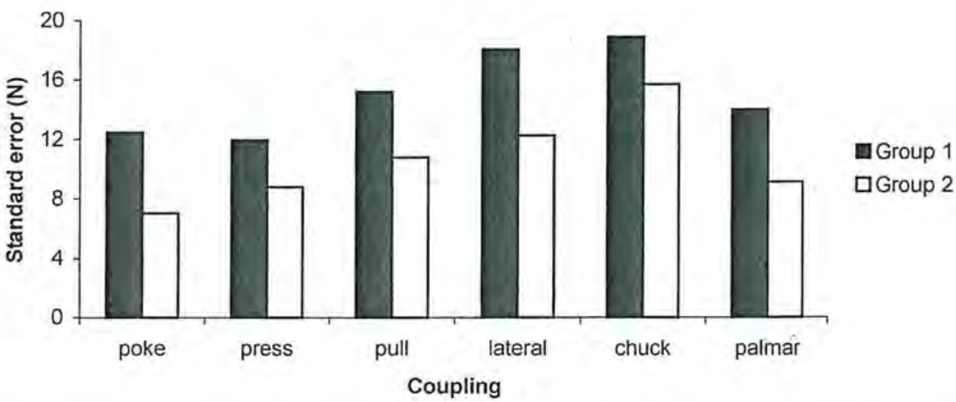


Figure 3. Comparison of regression model performance using data obtained from original participants (Group 1, $n = 100$) and from a second independent data set (Group 2, $n = 15$).

4.1. *Hand and finger strength*

Mean strength was larger for multi-digit compared to single digit couplings. Strength also differed between each coupling, and the overall magnitude appeared related to the direction of the force and the contact surfaces utilized. Not surprisingly, larger forces were produced as additional digits were employed. Although standard deviations increased proportional to increases in strength, coefficients of variation were relatively consistent, indicating that the variation relative to the mean was similar for all couplings regardless of the number of digits used or contact area. It should be noted that there was a slightly higher level of variation for the single digit couplings, possibly due to interindividual differences in postures maintained during these couplings. These couplings may also be intrinsically more variable between participants.

While no data on single finger strength could be found in the literature, several existing studies allow for comparison of multi-digit and grip strength with the present work. In comparison to the results of two large scale comprehensive studies, Mathiowetz *et al.* (1985) and Imrhan (1989), the present data are similar in terms of both means and variability (table 4). Differences between the three data sets may have been due to individual differences or procedural variations between the studies. For example, Imrhan (1989) collected data on participants between 18 and 40 years of age, which was more limited than either of the other studies.

4.2. *Correlations*

Correlations between and among the grip and finger strengths and anthropometric measures revealed substantial multicollinearity, while also providing an indication of the relationships among these measures. Correlations among anthropometric measures were typically high ($r = 0.51-0.98$), as has been demonstrated in earlier research (e.g. Webb Associates 1978, Cheverud *et al.* 1990, Kroemer *et al.* 1990). Only moderate correlations ($r = 0.31-0.67$), however, were found between finger strength and the anthropometric measures of the hand and arm. Similarly, moderate correlations ($r < 0.56$) between anthropometry and strength were found by Laubach and McConville (1969) and Chaffin *et al.* (1977), where anthropometric measures were used to predict a composite static strength (mean of 12 strength measures). Imrhan and Rahman (1995) also found low correlations ($r < 0.50$) between multi-digit strength and anthropometric measures (stature, body mass, hand length and hand breadth).

4.3. *Age and gender differences in finger strength*

The gender effect was significant for all six couplings, with males producing consistently larger forces than females. The magnitude of the differences, with females at ~70% of males across couplings, was comparable to gender differences found in other studies (e.g. Roebuck *et al.* 1975, Webb Associates 1978, Berg *et al.* 1988, Kanis 1993).

In contrast to gender, the main effect of age was not significant for any of the finger couplings. Differences within couplings ranged from ~1% to ~9% (1–7 N). In addition, the coefficients of variation were similar, though with slightly less variability in the 30–39 year old age group. The small sample sizes of the age groups limited the statistical power of these tests. The consistency among all age groups suggests the potential for universal design of hand tools and hand intensive workstations if strength is the only factor being considered. Multiple designs, stipulating different hand/finger force requirements, may not be necessary for individuals in different age ranges.

Although the age effect was not found to be significant in either the MANOVA or ANOVA, some trends were evident. Hand strengths were slightly (~10%) higher in the middle age group vs. the younger group, and slightly (~5%) lower in the oldest age group vs. the middle group. This trend is consistent with other studies (e.g. Swanson *et al.* 1970, Petrofsky and Lind 1975, Mathiowetz *et al.* 1985, Hallbeck and McMullin 1993), but should be verified with larger participant numbers over 30, and particularly in the 40 + age group. In addition, cause and effect could not be addressed in this cross-sectional study, in which the trends associated with age may simply be due to the individuals that participated in this research. Changes in strength may also be due to any number of environmental and developmental factors.

Compared to reported declines in overall strength (mean of trunk extension, trunk flexion, handgrip, knee extension, and elbow flexion) of approximately 20% (Viitasalo *et al.* 1985), the decline for the hand and fingers appeared to be minimal

Table 4. A comparison of multi-digit and grip strength from the present study and two previous studies. Coefficients of variation (%) are provided in parentheses.

	Present study		Mathiowetz (1985a)		Imrhan (1989)	
Coupling	Males (n = 50)	Females (n = 50)	Males (n = 288)	Females (n = 295)	Males (n = 40)	Females (n = 30)
Lateral (N)	97.02 (28.52)	64.84 (27.02)	109.69 (19.11)	72.68 (19.02)	92.21 (13.00)	63.77 (17.00)
Palmar (N)	62.88 (30.54)	45.45 (30.59)	75.80 (24.12)	50.83 (22.81)	71.61 (22.00)	46.11 (24.00)
Chuck (N)	95.37 (29.63)	64.13 (31.10)	104.34 (21.79)	72.68 (23.31)	92.21 (19.00)	68.67 (23.00)
Grip (N)	452.44 (22.75)	288.91 (21.23)	465.53 (27.20)	279.59 (27.27)	487.56 (19.00)	308.03 (24.00)

within this study. As discussed by Backman *et al.* (1995), the effect of age on muscle strength depends on the muscles being investigated. A decline in muscular strength reduces a person's capability, and may increase the risk of injury when tasks are performed that have high force requirements. If indeed there is a selective retention of hand or finger capabilities with age, then shifting older employees to more hand intensive tasks and away from heavy manual labour may be possible without adverse physical consequences. This is only true if there are no extenuating factors that would make such work difficult, for example, arthritis or decreased visual acuity.

4.4. *Prediction of finger strength*

Single-digit strength could only be predicted with moderate accuracy when using grip strength and anthropometric measures as possible predictor variables (R^2-adj = 0.34 – 0.44). Marked improvement in predictions of single digit strength was achieved using multi-digit strength (R^2-adj = 0.52 – 0.65). The performance of regression models based solely on multi-digit strengths was similar to models that also included grip strength and anthropometry. Use of multi-digit strength alone to predict single digit strength appears to be a reasonable alternative to the use of anthropometry and grip strength when predicting single digit strength, and requires fewer measurements.

Predictions of multi-digit strength were relatively accurate when only grip strength and anthropometric measures were included in the set of possible predictor variables (R^2-adj = 0.45 – 0.59). Increased accuracy as compared to the single digit strengths may be attributed to the greater similarity in the muscles used for the multi-digit couplings and grip. Model performance (coefficient of determination) was consistent with results presented by Hallbeck *et al.* (1989), who only used hand length, hand breadth and finger length as predictor variables for the same multi-digit strengths.

A goal of this research was to develop regression models that could be used easily in a work environment. The emphasis, when generating and choosing models, was to have a minimal set of predictor variables, maximize consistency of predictor variables between models, include predictor variables that were easily obtained, and create models that provide a relationship between variables that was intuitive from a physiological standpoint (i.e. only positive parameters). The final set of models affords a simple method for estimating hand and finger strengths based on easily obtainable measures, albeit with some limit on accuracy. However, the models may not be generalizable to other postures or couplings. Direct measurement of multi-digit strengths is possible, however, provided the practitioner has access to a pinch gauge.

4.5. *Model evaluation*

Development and analysis of predictive models using one group of participants does not provide very strong support for the usefulness of the models. An independent verification was thus performed using data from an additional group of participants. Predictions of single and multi-digit strength generated during this assessment process were moderately accurate (R^2-adj = 0.53 – 0.68) using the selected models. Although the distribution of the participants used for evaluation resembled the original group, the variability within the group may have been less than that of the original group due to random selection of participants. This may in part account for the improved model performance during the evaluation process. Despite this, the good correspondence between measured and predicted strength values does support the use of the models presented.

4.6. *Summary and applications*

Minimizing the percentage of hand and finger strength required to perform a task has been recommended for reducing the risk of certain musculoskeletal disorders (Armstrong 1986). Normative data regarding hand and finger capabilities are needed to design tools and tasks to implement such recommendations. This study provides new results on finger exertion capacity in a variety of tasks (couplings), particularly those involving a single digit. Force capacities can be compared in order to determine the most appropriate design alternative. Caution should be taken when generalizing the data to forces exerted in non-neutral postures. Given the results obtained, gender differences in hand and finger strength must be considered, though age, within the range studied, may not be an important factor for the couplings investigated.

When direct measurement of peak finger forces is difficult or impossible, predictive models can provide estimates of strength. Several models were developed to predict finger strength during basic hand couplings from easily obtainable measures. While grip strength was included in all of the models selected, grip should not be used as a single indicator of hand strength. A wide variety of models were developed using several approaches, including multiple linear and stepwise regressions, principle components, ridge regression, and model averaging, with each demonstrating a fairly consistent predictive ability, but leaving ~50% of the variance unexplained. Increased predictive accuracy and reduction of unexplained variance requires the investigation of additional predictor variables, possibly other anthropometric measures or different hand strengths. Understanding and incorporating the effects of pain and motivation on strength may also prove useful. Nonetheless, given that errors were typically on the order of 10–15 N, at least some level of guidance can be provided by these data and models for task evaluation and design.

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