

**Finger force capability: measurement and prediction using
anthropometric and myoelectric measures**

Angela DiDomenico Astin

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Industrial and Systems Engineering

Dr. Maury A. Nussbaum, Chair

Dr. Karl H.E. Kroemer

Dr. Laura Wojcik

December 16, 1999

Blacksburg, Virginia

Keywords: finger strength, pinches, electromyography, prediction

**Finger force capability: measurement and prediction using
anthropometric and myoelectric measures**

Angela DiDomenico Astin

(ABSTRACT)

Hand and finger force data are used in many settings, including industrial design and indicating progress during rehabilitation. The application of appropriate work design principles, during the design of tools and workstations that involve the use of the hand and fingers, may minimize upper extremity injuries within the workplace. Determination and integration of force capabilities and requirements is an essential component of this process. Available data in the literature has focused primarily on whole-hand or multi-digit pinch exertions. The present study compiled and examined maximal forces exerted by the fingers in a variety of couplings to both enhance and supplement available data. This data was used to determine whether finger strength could be predicted from other strength measures and anthropometry. In addition, this study examined whether exerted finger forces could be estimated using surface electromyography obtained from standardized forearm locations. Such processes are of utility when designing and evaluating hand tools and human-machine interfaces involving finger intensive tasks, since the integration of finger force capabilities and task requirements are necessary to reduce the risk of injury to the upper limbs.

Forces were measured using strain gauge transducers, and a modification of standard protocols was followed to obtain consistent and applicable data. Correlations within and among maximum finger forces, whole-hand grip force, and anthropometric measures were examined. Multiple regression models were developed to determine the feasibility of predicting finger strength in various finger couplings from more accessible measures. After examining a wide variety of such mathematical models, the results suggest that finger strength can be predicted from easily obtained measures with only moderate accuracy (R^2 -adj: 0.45 – 0.64; standard error: 11.95N – 18.88N). Such models,

however, begin to overcome the limitations of direct finger strength measurements of individuals.

Surface electrodes were used to record electromyographic signals collected from three standardized electrode sites on the forearm. Multiple linear regression models were generated to predict finger force levels with the three normalized electromographic measures as predictor variables. The results suggest that standardized procedures for obtaining EMG data and simple linear models can be used to accurately predict finger forces (R^2 -adj: 0.77 – 0.88; standard error: 9.21N – 12.42N) during controlled maximal exertions. However, further work is needed to determine if the models can be generalized to more complex tasks.

ACKNOWLEDGMENTS

Heartfelt thanks for the academic and collegial support provided by Drs. Maury A. Nussbaum, Karl H. E. Kroemer, and Laura Wojcik throughout the development, planning, and execution of this research. Only with their assistance and guidance was this project possible. Special thanks to Dr. Nussbaum for his support as committee chair and his constant accessibility and patience throughout the course of this project.

My sincere gratitude goes to Ron Spencer for helping make a difficult task a little easier. Also thanks to Gary Olacsi for his support, encouragement, and friendship especially during the stressful times. Heartfelt gratitude and appreciation to Suzanne Stevens who knows what it means to be a good friend. I could not have made it this far without her support, understanding, and encouragement.

Finally, my love and deepest thanks go to my husband, Michael, who may not have always understood what I was doing but has always stood by me to give me a smile and a hug, during good times and bad. He has always believed in me and been willing to sacrifice for me. The completion of this thesis was second only to Michael and our love.

TABLE OF CONTENTS

ABSTRACT	II
ACKNOWLEDGMENTS.....	IV
LIST OF FIGURES.....	VII
LIST OF TABLES	X
HAND AND FINGER FORCE DATA COLLECTION AND PREDICTION.....	1
1. INTRODUCTION.....	1
2. REVIEW OF LITERATURE.....	3
3. METHODS AND MATERIALS	9
3.1 OVERVIEW	9
3.1.1 Experimental objectives	10
3.1.2 Experimental hypotheses.....	10
3.2 EXPERIMENTAL DESIGN	10
3.2.1 Anthropometric Measures.....	10
3.2.2 Experimental Conditions.....	11
3.2.3 Maximum Voluntary Force Measures.....	15
3.3 PARTICIPANTS	15
3.4 APPARATUS AND MATERIALS	16
3.5 EXPERIMENTAL PROCEDURES	18
3.6 DATA ANALYSIS PROTOCOL	21
4. RESULTS.....	23
4.1 ANTHROPOMETRIC DATA.....	23
4.2 HAND AND FINGER STRENGTH.....	24
4.3 CORRELATIONS	25
4.4 MULTIVARIATE (MANOVA) AND UNIVARIATE ANALYSIS OF VARIANCE (ANOVA).....	27
4.5 MODELS FOR PREDICTION OF FINGER STRENGTH.....	29
4.5.1 Multiple Linear and Stepwise Regression.....	30
4.5.2 Model Averaging.....	38
4.6 RIDGE REGRESSION.....	39
5. DISCUSSION	40
5.1 ANTHROPOMETRIC DATA.....	41
5.2 HAND AND FINGER STRENGTH.....	41
5.3 CORRELATIONS	43
5.4 AGE AND GENDER DIFFERENCES IN FINGER STRENGTH.....	43
5.5 REGRESSION.....	44

5.5.1	Multiple Linear and Stepwise Regression.....	44
5.5.2	Model Averaging.....	46
5.6	RIDGE REGRESSION.....	47
5.7	DERIVED REGRESSION MODELS.....	47
5.8	APPLICATIONS.....	48
5.9	LIMITATIONS OF STUDY.....	49
5.10	FUTURE AREAS OF RESEARCH.....	50
6.	CONCLUSIONS.....	51
FORCE-EMG RELATIONSHIP DURING COMMON HAND COUPLINGS		52
1.	INTRODUCTION.....	52
2.	REVIEW OF LITERATURE.....	54
3.	METHODS AND MATERIALS	59
3.1	OVERVIEW	59
3.2	EXPERIMENTAL DESIGN.....	59
3.2.1	Experimental Conditions.....	59
3.3	PARTICIPANTS	59
3.4	APPARATUS AND MATERIALS	60
3.4.1	Maximum Voluntary Force Measures.....	60
3.4.2	Electromyographic (EMG) Activity Level.	61
3.5	EXPERIMENTAL PROCEDURES	61
3.6	DATA ANALYSIS PROTOCOL	65
4.	RESULTS.....	67
4.1	GRAPHICAL DATA	67
4.2	MODELS FOR PREDICTION OF FINGER FORCES	68
4.3	MODEL PERFORMANCE	73
4.4	MODEL PARAMETERS.....	75
5.	DISCUSSION	80
5.1	GENERAL COMMENTS	80
5.2	MODELS FOR PREDICTION OF FINGER FORCES	81
5.3	LIMITATIONS.....	83
5.4	COMPARISONS TO OTHER RESEARCH.....	84
5.5	APPLICATIONS.....	84
5.6	FUTURE RESEARCH AREAS	85
6.	CONCLUSIONS.....	87
REFERENCES.....		88
VITA		93

LIST OF FIGURES

FIGURE 1. CLASSIFICATION OF FORCE EXERTIONS INVESTIGATED WITHIN THIS STUDY.	9
FIGURE 2. ILLUSTRATION OF THE SINGLE DIGIT POKE COUPLING USING THE INDEX FINGER.....	12
FIGURE 3. ILLUSTRATION OF THE SINGLE DIGIT 90-DEGREE DISTAL PAD PULL USING INDEX FINGER.	12
FIGURE 4. ILLUSTRATION OF THE SINGLE DIGIT 180-DEGREE DISTAL PAD PRESS USING INDEX FINGER.....	13
FIGURE 5. ILLUSTRATION OF THE MULTI-DIGIT LATERAL PINCH COUPLING.	13
FIGURE 6. ILLUSTRATION OF THE MULTI-DIGIT PALMAR PINCH COUPLING.....	14
FIGURE 7. ILLUSTRATION OF THE MULTI-DIGIT THREE-JAW CHUCK PINCH COUPLING.	14
FIGURE 8. ILLUSTRATION OF THE WHOLE HAND POWER GRASP COUPLING.....	15
FIGURE 9. RELATIONSHIP OBTAINED BETWEEN APPLIED LOAD AND VOLTAGE OUTPUT OF STRAIN GAUGE TRANSDUCER (IN HALF-BRIDGE CONFIGURATION).....	17
FIGURE 10. RELATIONSHIP OBTAINED BETWEEN APPLIED LOAD AND VOLTAGE OUTPUT OF STRAIN GAUGE TRANSDUCER (IN FULL-BRIDGE CONFIGURATION).	18
FIGURE 11. EXAMPLE OF AN ACCEPTABLE FORCE EXERTION TRIAL.	20
FIGURE 12. EXAMPLE OF AN UNACCEPTABLE FORCE EXERTION TRIAL, IN WHICH THE FORCE WAS RELEASED TOO QUICKLY.	20
FIGURE 13. AVERAGE STRENGTHS FOR FEMALES AND MALES FOR EACH COUPLING. AVERAGE FEMALE STRENGTHS ARE GIVEN AS A PERCENTAGE OF THE MALE VALUES.	28
FIGURE 14. AVERAGE STRENGTH FOR EACH COUPLING ACROSS FIVE AGE CLASSIFICATIONS.....	29
FIGURE 15. RELATIONSHIP BETWEEN HAND LENGTH AND PALMAR PINCH STRENGTH. A LINEAR RELATIONSHIP, AS SEEN HERE, WAS TYPICAL FOR ALL DEPENDENT AND INDEPENDENT VARIABLE COMBINATIONS.	30
FIGURE 16. COMPARISON OF REGRESSION MODELS USING ALL PREDICTOR VARIABLES AND SIGNIFICANT INTERACTIONS.....	31
FIGURE 17. COMPARISON OF STANDARD ERRORS FOR REGRESSION MODELS USING ALL PREDICTOR VARIABLES AND SIGNIFICANT INTERACTIONS.....	31
FIGURE 18. R^2 -ADJ VALUES CORRESPONDING TO ESTIMATIONS OF SINGLE DIGIT STRENGTH FROM PINCH STRENGTH.	33
FIGURE 19. STANDARD ERROR VALUES CORRESPONDING TO ESTIMATIONS OF SINGLE DIGIT STRENGTH FROM PINCH STRENGTH.....	34
FIGURE 20. COMPARISON OF R^2 -ADJ ASSOCIATED WITH REGRESSION MODELS USING PRINCIPAL COMPONENTS AS PREDICTOR VARIABLES.....	36
FIGURE 21. COMPARISON OF STANDARD ERRORS ASSOCIATED WITH REGRESSION MODELS USING PRINCIPAL COMPONENTS AS PREDICTOR VARIABLES.	36
FIGURE 22. R^2 -ADJ FOR REGRESSION MODELS CONSIDERING GENDER CATEGORIZATIONS.....	37
FIGURE 23. STANDARD ERRORS FOR REGRESSION MODELS CONSIDERING GENDER CATEGORIZATIONS.	38

FIGURE 24. ELECTRODE PLACEMENT FOR RECORDING FLEXOR I SIGNALS.	63
FIGURE 25. ELECTRODE PLACEMENT FOR RECORDING FLEXOR II SIGNALS.	64
FIGURE 26. ELECTRODE PLACEMENT FOR RECORDING EXTENSOR SIGNALS.	64
FIGURE 27. NORMALIZED FORCE (NFORCE) AND NORMALIZED ELECTROMYOGRAPHIC CURVES (FLEXORS I – NEMG1; EXTENSORS – NEMG2; FLEXORS II – NEMG3) FOR A TYPICAL FORCE EXERTION (LATERAL PINCH).....	67
FIGURE 28. MUSCLE ACTIVITY PRESENT AT VARYING LEVELS OF FORCE DURING THE INCREASE AND DECREASE OF FORCE.	68
FIGURE 29. MEASURED VERSUS PREDICTED FORCES (PERCENT OF MAXIMUM) FOR THE WHOLE TASK (R^2 -ADJ = 0.95, STANDARD ERROR = 8.35N). A LINEAR REGRESSION LINE HAS BEEN SUPERIMPOSED ON THE CURVE FOR COMPARISON.	70
FIGURE 30. MEASURED VERSUS PREDICTED FORCES (PERCENT OF MAXIMUM) FOR THE PORTION OF THE TASK ASSOCIATED WITH AN INCREASE IN FORCE (R^2 -ADJ = 0.97, STANDARD ERROR = 6.73N). A LINEAR REGRESSION LINE HAS BEEN SUPERIMPOSED ON THE CURVE FOR COMPARISON.....	70
FIGURE 31. MEASURED VERSUS PREDICTED FORCES (PERCENT OF MAXIMUM) FOR THE PORTION OF THE TASK ASSOCIATED WITH A DECREASE IN FORCE (R^2 -ADJ = 0.97, STANDARD ERROR = 5.54N). A LINEAR REGRESSION LINE HAS BEEN SUPERIMPOSED ON THE CURVE FOR COMPARISON.....	71
FIGURE 32. NORMALIZED FORCE AND NORMALIZED EMG CURVES FOR A “BAD” FORCE EXERTION (90-DEGREE DISTAL PAD PULL).....	72
FIGURE 33. MUSCLE ACTIVITY PRESENT AT VARYING LEVELS OF FORCE DURING THE INCREASE AND DECREASE OF FORCE.	72
FIGURE 34. MEASURED VERSUS PREDICTED FORCE FOR THE PORTION OF THE TASK ASSOCIATED WITH AN INCREASE IN FORCE (R^2 -ADJ = 0.70, STANDARD ERROR = 6.82N).....	73
FIGURE 35. MEASURED VERSUS PREDICTED FORCE FOR THE PORTION OF THE TASK ASSOCIATED WITH A DECREASE IN FORCE (R^2 -ADJ = 0.64, STANDARD ERROR = 10.14N).	73
FIGURE 36. AVERAGE R^2 -ADJ VALUES FOR THE DIFFERENT COUPLINGS COMPARING ACROSS THE THREE EXERTION CLASSIFICATIONS.....	74
FIGURE 37. AVERAGE STANDARD ERROR VALUES FOR THE DIFFERENT COUPLINGS COMPARING ACROSS THE THREE EXERTION CLASSIFICATIONS.....	75
FIGURE 38. AVERAGE NUMBER OF SIGNIFICANT PARAMETERS INCLUDED IN THE REGRESSION MODELS FOR THE THREE EXERTION CLASSIFICATIONS.....	76
FIGURE 39. PERCENTAGE OF REGRESSION MODELS IN WHICH THE PARAMETERS WERE FOUND TO BE SIGNIFICANT WHEN CONSIDERING THE WHOLE EXERTION.	77
FIGURE 40. PERCENTAGE OF REGRESSION MODELS IN WHICH THE PARAMETERS WERE FOUND TO BE SIGNIFICANT WHEN CONSIDERING THE ASCENDING PORTION OF THE EXERTION.	77
FIGURE 41. PERCENTAGE OF REGRESSION MODELS IN WHICH THE PARAMETERS WERE FOUND TO BE SIGNIFICANT WHEN CONSIDERING THE DESCENDING PORTION OF THE EXERTION.	78

FIGURE 42. MEASURED AND PREDICTED FORCES FOR A SUBMAXIMAL TIME-VARYING EXERTION USING THE
POKE HAND COUPLING (R^2 -ADJ = 0.91; STANDARD ERROR = 7.9%). 85

LIST OF TABLES

TABLE 1. SUMMARY OF ANTHROPOMETRIC CHARACTERISTICS FOR ALL PARTICIPANTS AND CLASSIFIED BY GENDER.....	23
TABLE 2. SUMMARY OF STRENGTH AND VARIABILITY IN EACH OF THE FINGER COUPLINGS AND FOR SIMPLE GRIP ACROSS THE 100 SUBJECTS.	24
TABLE 3. SUMMARY OF STRENGTH AND VARIABILITY IN EACH OF THE FINGER COUPLINGS AND FOR SIMPLE GRIP CLASSIFIED BY GENDER.....	24
TABLE 4. SUMMARY OF STRENGTH AND VARIABILITY IN EACH OF THE FINGER COUPLINGS AND FOR SIMPLE GRIP CLASSIFIED BY AGE.	25
TABLE 5. PEARSON’S CORRELATION MATRIX (R) FOR STRENGTH MEASURES AND ANTHROPOMETRIC MEASUREMENTS	26
TABLE 6. PEARSON’S CORRELATION MATRIX (R) FOR ANTHROPOMETRIC MEASUREMENTS.....	27
TABLE 7. PEARSON’S CORRELATION MATRIX (R) FOR SINGLE DIGIT FORCE EXERTIONS VERSUS MULTI-DIGIT FORCES.....	27
TABLE 8. R ² -ADJ VALUES FOR MULTIPLE REGRESSION MODELS PREDICTING SINGLE FINGER STRENGTH FROM ONE MULTI-DIGIT STRENGTH AND GRIP STRENGTH.....	35
TABLE 9. A COMPARISON OF MULTI-DIGIT AND GRIP STRENGTH FROM THE PRESENT STUDY AND TWO PREVIOUS STUDIES. COEFFICIENTS OF VARIATION ARE PROVIDED IN PARENTHESES.....	42
TABLE 10. MEASURES OF ACCURACY (R ² -ADJ AND STANDARD ERROR) FOR SELECTED MODELS TO PREDICT THE SINGLE AND MULTI-DIGIT STRENGTH.....	48
TABLE 11. SUMMARY CHARACTERISTICS FOR THE REGRESSION PARAMETERS DETERMINED WHEN ANALYZING EACH COUPLING FOR THE WHOLE EXERTION (B ₁ :FIRST GROUP OF FLEXORS; B ₂ :EXTENSORS; B ₃ :SECOND GROUP OF FLEXORS).....	79

HAND AND FINGER FORCE DATA COLLECTION AND PREDICTION

1. INTRODUCTION

Consideration of hand and finger force capability is essential during industrial design of hand intensive tasks and the evaluation of improvements occurring during rehabilitation. Hand intensive tasks require diverse and sometimes extreme levels of force exertion depending on the movements involved. Finger force capabilities should be considered when such tasks are designed in an effort to minimize discomfort and injuries of the upper extremities. Furthermore, it is necessary to understand the capabilities of the hand and fingers in order to evaluate the level of disability caused by existing injuries and progress made during recovery. Understanding the physical capabilities and limitations of individuals is therefore necessary to optimize performance and minimize injury.

Cumulative trauma disorders (CTDs) have become a major concern for industry in the recent past. CTDs are caused by the chronic effects of repetitive actions on the tendons, tendon sheaths, muscles and nerves of the upper extremities (Armstrong, 1986a). Movements and exertions of the upper extremities, such as reaching, gripping and pinching, combined with repetition in a forceful and/or awkward manner are known contributing factors to the precipitation and aggravation of CTDs (Palanisami, Narasimhan, and Fernandez, 1994). Reported occupational risk factors of various types of CTDs, including carpal tunnel syndrome and tenosynovitis are described in Armstrong, Foulke, Joseph, and Goldstein (1982). Armstrong (1986a) asserts that CTDs of the upper extremities are a primary cause of lost time and Workers' Compensation in hand-intensive industries.

Upper extremity injuries can be minimized through intervention and the application of appropriate work design principles. Armstrong (1986b) reports that the known occupational risk factors for CTDs include repetitive and forceful exertions, mechanical stresses, extreme postures, vibration and low temperature. The integration of human strength capabilities and minimization of force requirements during the design phase of hand intensive tasks may reduce the risk of occupational injuries, including CTDs, and the costs associated with them (Armstrong, 1986a; Palanisami et al., 1994).

Past research has focused on whole-hand grip strength and how variables such as gender and handle width affect peak grip capability. There are few investigations, however, which have specifically addressed the force capabilities of the fingers in practical situations such as pinching and poking, and there is very little research that has examined the force capabilities of single digits in various couplings with handles and levers. Data describing finger force capacity has direct application in the design of human-machine interfaces involving the whole hand or single digits. If the data was available, appropriate, yet minimal force requirements could be integrated into industrial design. The first goal of this study was to compile a database describing maximum finger forces (strength) in several single and multi-digit couplings. This data, in part, supplements existing results in the literature and also provides strength data regarding the index finger during single digit couplings.

Acquisition of single digit force capabilities can require specialized equipment and environments that are not easily integrated into a working environment. A practical question arises as to whether force capability in specific finger couplings can be *predicted* from other more accessible measures and thus allow the practitioner to gather the pertinent data without a significant interruption of normal tasks while maintaining relatively low costs. If so, then the limitations of direct finger strength measurements will be overcome. The second experimental goal was to determine the inter-correlations within and among maximum finger strengths, simple grip strength, and anthropometry. Predictive models were developed using multiple linear regression in addition to the exploration of other statistical methods (e.g. principal components). The goal in developing these models was to assess the feasibility of predicting finger strength from easily obtained anthropometric data and grip strength. Such models help overcome the limitations of direct finger strength measurements of individuals.

2. REVIEW OF LITERATURE

Individuals use their hands and fingers everyday at work and in the home. Knowledge of the force capabilities of the hand and fingers can facilitate the design of better tools and controls, and provide valuable data for comparison to current exertion levels of injured workers to determine the extent of an injury or the level of recovery.

Investigations concerning the strength capabilities of the hand began with explorations of grip strength. Napier (1956) identified and classified applications of various hand couplings using grips and multi-digit pinches. In (1970), Schmidt and Toews, using a Jamar dynamometer, reported average grip strength for males as 504.2 N and that of females as 311.0 N. A regression model with predictor variables that included age, weight and height was derived with a reported predictive reliability of 95% for grip strength. Swanson, Matev, and de Groot (1970), also using a Jamar dynamometer, found comparable average male grip strength of 467.0 N and that of females as 241.3 N. However, strength measurements can vary depending on the instructions provided to the individual and the postures maintained during the force exertions. Mathiowetz, Weber, Volland, and Kashman (1984) investigated the reliability of grip and pinch strength evaluations by taking measurements that were separated in time by more than one day. After recording strength measurements for 27 women, it was concluded that standardizing positioning and instructions could achieve high retest reliability. Furthermore, the average of three trials was found to be the most reliable and accurate measure under these circumstances, as compared to one trial or the highest value of the three trials.

Research pertaining to the strength of the hand has continued and expanded to include additional measurements, such as pinch strengths. A number of these studies still include the collection of grip strength data in their results (Imrhan, 1989; Kinoshita, Kawai, Ikuta, and Teraoka, 1996; Mathiowetz, Kashman, Volland, Weber, Dowe, and Rogers, 1985a; Mathiowetz, Rennells, and Donahoe, 1985b; Palanisami et al., 1994; Radwin, Oh, Jensen, and Webster, 1992). Extensive data on the strength of the fingers during multi-digit exertions is available within the literature. Previous multi-digit strength studies have been conducted to gather peak and sustained strength data and to

determine what factors may influence multi-digit strength. An overview of these studies is provided below.

Previous experimentation has included the collection of force data for various pinch exertions. Mathiowetz, et al. (1985a) determined clinical norms for adults of varying ages using a large sample (n=628) of subjects. Their analysis focused on differences in maximum voluntary contractions produced among individuals in several age groups and of different hand dominance. Clinical norms were provided for 12 age groups for both sexes. No significant difference was found in the forces produced by right and left hand dominant individuals.

Imrhan (1989) collected pinch strength data to determine quantitative relationships among different types of (maximal) pinch forces. He concluded that since composite pinches, such as lateral and three-jaw chuck, produced greater strengths, pinch handles should be made large enough to accommodate these pinches. In addition, differences between the sexes and hand laterality were investigated, with results showing that the absolute strength differences between the sexes are slight in children, greatest in adults, and decrease slightly in the elderly. Furthermore, pinches with the right hand are slightly greater (106%) than pinches produced by the left hand of right hand dominant individuals. Finally, no significant correlations between strength and anthropometry (stature, body weight, hand length, hand breadth) were found.

Procedures used during data collection appear to affect the results of strength measurement. Caldwell, Chaffin, Dukes-Dobos, Kroemer, Laubach, Snook, and Wasserman (1974) demonstrated that the standardization of procedures is necessary for accurate comparison of research findings. Procedural recommendations included the elimination of any instantaneous feedback during the exertions and a minimum of two minutes of rest between exertions. The commonly used “Caldwell Regimen” dictates that participants increase force to maximum in approximately one second, after which a steady exertion is maintained for four seconds. This steady exertion must remain within a $\pm 10\%$ band to be considered an acceptable trial. The force is then decreased over the final one second period. Strength is determined as the average of the first three seconds of the steady exertion (Caldwell et al., 1974). These procedural details were determined after comparison of three sets of instructions (“jerk”, “increase”, “hold”). The “hold”

technique was the most reliable, providing the least variable results among repeated measures.

Despite the suggestions of Caldwell et al. (1974), no consensus has been established for the procedures used in strength measurements of the hand and fingers. Berg, Clay, Fathallah, and Higginbotham (1988) examined the effects of instructions on three multi-digit pinches and Williamson and Rice (1992) re-evaluated the Caldwell Regimen for grip. Berg, et al. (1988) showed that it is difficult for participants to maintain forces within the recommended $\pm 10\%$ band during pinch strengths and that peak strength differed according to the duration of effort. They recommended that the steady exertion be reduced to two or three seconds. Williamson and Rice (1992) tested three sets of instructions for measuring grip strength: (1) sudden maximal contraction, maintained; (2) sudden maximal contraction; and (3) built-up force, maintained. They found that participants were able to achieve the band requirements when grip strength was being measured but alterations in instruction significantly affected the forces produced. Furthermore, Mathiowetz (1985a) used a set of spoken instructions that was not based on the Caldwell Regimen.

The configuration and location of the fingers are not solely responsible for the magnitude of pinch force exertions. It is important to note that the posture of the participants and the orientation of relevant body parts (e.g. wrist and elbow) can affect the levels of force produced. The American Society of Hand Therapists (Fess and Moran, 1981) recommends that participants are positioned with feet flat on the floor, back straight and supported by a backrest, shoulder adducted and neutrally rotated, elbow at 90 degrees, and forearm supported in a neutral position. Many of the existing studies on hand and finger strength have utilized this standard positioning (e.g. Dempsey and Ayoub (1996), Mathiowetz et al. (1985b), and Williamson and Rice (1992)). However, there are exceptions, such as Imrhan (1989), who used a slightly modified position with the shoulder flexed at 30 degrees and the humerus slightly abducted. The recommended posture was altered so the individuals' fingers were positioned on the pinch gauge just below horizontal.

Positioning of the arm can significantly affect the maximum force exertions produced during grip and pinch exertions. Mathiowetz et al. (1985a) examined the affect

of elbow position on grip and lateral pinch strength. These strength values were significantly higher when the elbow was in a 90-degree flexed position as compared to the fully extended position. Results supported the use of the standardized position that includes the elbow at 90-degree flexion as recommended by the American Society of Hand Therapists. Palanisami et al. (1994) examined the affect of body, elbow and forearm postures on peak three-jaw chuck pinch strength. Variations due to posture for these pinch force levels were as much as 21% for peak three-jaw chuck pinch strength. Standing posture with the elbow adducted and forearm mid-pronated was associated with the highest forces (80.4 N) while sitting without armrests with the shoulder ½ abducted and forearm pronated produced the least (63.7 N).

In addition to the posture of the whole body and the position of the arm, many additional variables affect the force capabilities of individuals during pinch exertions. The influence of gender, grasp type, pinch width, and wrist position on sustained pinch strength was investigated by Dempsey and Ayoub (1996). They used the modified Caldwell Regimen recommended by Berg at al. (1988) and postures recommended by the American Society of Hand Therapists. Females were 62.9% as strong, on average, as the male subjects when considering all pinch exertions. The lateral grasp type allowed the greatest force exertions, 13.2% greater than the three-jaw chuck followed by the palmar pinch. Changes in pinch width resulted in a 16.5% reduction in strength while wrist position caused a reduction of 24% in strength. The 5cm pinch width and the neutral wrist positions were the optimal settings for producing the largest pinch strengths.

Imrhan and Rahman (1995) also studied the effects of pinch width on pinch strengths of adult males. Pinch strength varied up to 3.2 times with respect to pinch width, with larger pinch widths (10.4 – 14.0 cm) reducing strength capabilities. Small to moderate pinch widths (2.0 – 9.2 cm) did not have as strong an affect on pinch strengths as did wider pinch widths. The type of pinch was also found to significantly affect pinch strength, with the three-jaw chuck pinch producing the greatest force exertions.

Finger force capabilities are not limited to the study of pinch data but also include single digit strengths and forces produced by the individual fingers during whole hand exertions. Radwin et al. (1992) studied single digit forces during submaximal five-finger static pinches. Average forces produced by the individual fingers depended on the

weight of the load being held. The index and middle fingers exerted 1 N to 5 N of force greater than that of the ring and small fingers across all pinch conditions. Additionally, Kinoshita et al. (1996) studied individual finger forces generated on a grasped object during shaking actions. The index finger contributed the largest percent of the force needed to maintain the five-finger pinch regardless of shaking direction. Variations in the shaking direction affected the contribution of the remaining fingers. Contributions of the ring and small finger were greatest during horizontal and mediolateral directions. Different finger force contributions and coordination are thus required when pinching is combined with shaking of an object.

One possible explanation for the relative lack of research examining single digit strength is that measuring finger forces within a working environment can be time consuming and difficult, particularly if data is needed for each employee performing hand intensive tasks. Although portable and easily operated grip and pinch gauges are commercially available, a gauge has not been developed that can accurately measure single digit strength and is also portable and easy to use.

Prediction of finger forces from easily obtainable measures would minimize the effort needed to gather finger strength measurements and eliminate the need for the portable finger force gauges. Hallbeck, Rice, Fathallah, and Williams (1989) attempted to predict pinch strengths based on hand length, hand breadth, and finger length. The predictor variables chosen did lead to models that estimated pinch strength with acceptable accuracy, in addition, the authors recommended that further research be performed with additional predictor variables. In a study by Rice, Williamson, and Sharp (1998), it was suggested that forearm diameter may be a reliable predictor of grip strength. Grip strength was predicted from 20 anthropometric measures and four strength measures and it was found that forearm circumference (flexed) was the best predictor of grip strength obtained during a quick build-up procedure, and forearm circumference (relaxed) was the best predictor of grip strength during an immediate maximal exertion procedure. The predictive value of the forearm circumference is likely due to the inclusion of many hand muscles within the forearm (Rice et al., 1998). Grip and pinch exertions utilize similar muscles so it is possible that forearm circumference may also be a reliable predictor of single and multi-digit strength.

A variety of single and multi-digit exertions commonly used in industrial tasks having some form of hand- or finger-machine interface were included in the set of experimental tasks within this study. Subjects performed three single digit force exertions, three multi-digit force exertions and one grip exertion (see Methods). The multi-digit efforts (lateral pinch, three-jaw chuck pinch, palmar pinch) were as described by Mathiowetz et al. (1985a). Kroemer (1986) and Jacobson and Sperling (1976) propose additional descriptions of couplings between the hand and controls that involve single and multiple digits, including couplings that loosely describe the single digit couplings included in this study. The set of hand-handle positions describes the primary positions that the hand maintains during force exertions.

The couplings that were examined in this study were based on the positions and actions that are commonly required during hand intensive tasks within the workplace. The scientific literature has included the lateral pinch, palmar pinch and three-jaw chuck pinch as the three most commonly used pinches by a person within a working environment. The fact that many hand intensive tasks require pushing buttons, sliding levers, and other movements that only use the index finger, motivated investigations of such tasks, in addition to pinching tasks. Appropriate data describing single digit exertions while performing these tasks, however, is not currently available.

3. METHODS AND MATERIALS

3.1 Overview

This project determined the maximum voluntary force capabilities (strength) 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. Specific couplings were chosen to reproduce exertions that are common during hand intensive tasks found in many workplaces (e.g., inserting fasteners and pushing buttons).

Terminology in the existing literature is at times inconsistent regarding the description of pinches. Pinches similar to those used in this study are referred to in many ways, including but not limited to: writing grip, thumb-fingertip grip, thumb-finger palmar grip, thumb-forefinger side grip, precision grip, tip pinch and key pinch. The seven couplings investigated in this research were divided into prehensile and non-prehensile couplings (Figure 1). Prehensile couplings involve wrapping around with the whole hand and include the power grasp. Non-prehensile couplings are subdivided into multi-digit (lateral pinch, palmar pinch, three-jaw chuck pinch) and single digit (poke, 90-degree distal pad pull, 180-degree distal pad press) couplings.

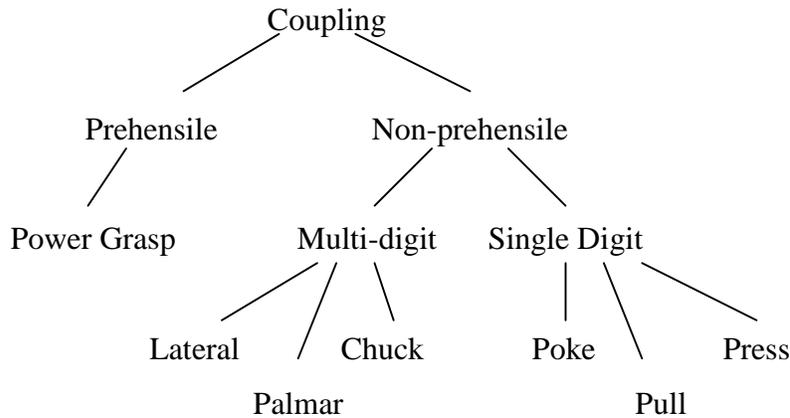


Figure 1. Classification of force exertions investigated within this study.

Anthropometric measures were collected from each individual, and the relationships between these measures and hand and finger forces examined. In addition,

the feasibility of predicting maximum finger forces from easily obtainable measures (e.g., grip strength and anthropometric measures) was investigated.

3.1.1 Experimental objectives

The focus of this research was to:

1. Compile hand and finger strength from a large sample, representative of a working population, and consisting of individuals of varying ages. This supplemented existing data in the scientific literature and provided some data not previously available.
2. Determine whether finger strength could be predicted from other strength measures and anthropometry.

3.1.2 Experimental hypotheses

Hypothesis 1: Consistent gender and age differences in finger strength exist across several different couplings.

Hypothesis 2: Finger strength can be predicted from more easily obtainable measures, specifically anthropometric data and grip strength.

3.2 Experimental Design

The experiment was a full factorial, repeated measures design. Subjects performed maximum voluntary exertions in seven couplings with three trials per coupling for a total of 21 trials. There was one set of experimental conditions consisting of seven hand couplings and one dependent variable, maximal voluntary force. Additionally, anthropometric measures were collected for subsequent generation of predictive models. In order to prevent any confounded influences related to ordering (e.g., learning), conditions were presented in a totally randomized order.

3.2.1 Anthropometric Measures.

Nine anthropometric measures were obtained from each participant: weight, height, hand length, hand breadth, wrist breadth, wrist circumference, forearm circumference relaxed, forearm circumference flexed, and forearm-hand length. Values were recorded as part of the subject data, and to the nearest millimeter. Descriptions of

each measure were adapted from the Anthropometric Source Book Volume II: A Handbook of Anthropometric Data (Webb Associates, 1978):

1. Height (cm): stature; distance from the top of the head to the ground
2. Weight (kg): lightly clothed weight (no shoes)
3. Hand Length (cm): distance from the base of the hand to the top of the middle finger measured along the long axis of the hand
4. Hand Breadth (cm): breadth of the hand as measured across the distal ends of the metacarpal bones
5. Wrist Breadth (cm): distance between the radial and ulnar styloid prominences of the wrist measured with the flesh compressed
6. Wrist Circumference (cm): circumference of the wrist at the level of the tip of the styloid process of the radius
7. Forearm-hand Length (cm): distance from the tip of the elbow to the tip of the longest finger
8. Relaxed Forearm Circumference (cm): maximum circumference of the lower arm with elbow at 90 degrees, the upper arm vertical
9. Flexed Forearm Circumference (cm): maximum circumference of lower arm with elbow at 90 degrees, upper arm horizontal, fist clenched

3.2.2 Experimental Conditions.

Seven hand couplings were chosen to simulate a wide variety of hand intensive tasks that are typically performed in industrial settings. For example, pushing buttons, sliding levers, and inserting fasteners all require single or multi-digit couplings similar to those investigated. Furthermore, the utility of these measurements was reinforced because of previous use of these couplings within the literature (Berg et al., 1988; Dempsey and Ayoub, 1996; Hallbeck et al., 1989; Kroemer, 1986; Mathiowetz et al., 1985a). The specific couplings that were investigated are described and illustrated below.

1. Poke (index finger): The forearm and wrist were in a position such that the palm was down and the index finger was in line with the straight wrist. Force was exerted at the tip of the index finger (such that the fingernail did not interfere with the force exertion). Force was exerted in line with the tested digit (Figure 2).



Figure 2. Illustration of the single digit poke coupling using the index finger.

2. 90-degree Distal Pad Pull (index finger): The forearm and wrist were in a position such that the palm was down. Force was exerted at the pad of the index finger while the finger was bent at approximately a 90-degree angle at the middle knuckle. The finger ‘hooked’ the gauge (Figure 3).



Figure 3. Illustration of the single digit 90-degree distal pad pull using index finger.

3. 180-degree Distal Pad Press (index finger): The forearm and wrist were in a position such that the palm was down and the index finger was in line with the straight wrist. Force was exerted at the pad of and perpendicular to the index finger (Figure 4).



Figure 4. Illustration of the single digit 180-degree distal pad press using index finger.

4. Lateral Pinch: The forearm and wrist were in a position such that the palm was inward, toward the body. 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 (Figure 5).



Figure 5. Illustration of the multi-digit lateral pinch coupling.

5. Palmar Pinch: The forearm and wrist were in a position such that the palm was down. Force was exerted between the pad of the index finger and the pad of the thumb, through the centers of the opposing pads (Figure 6).

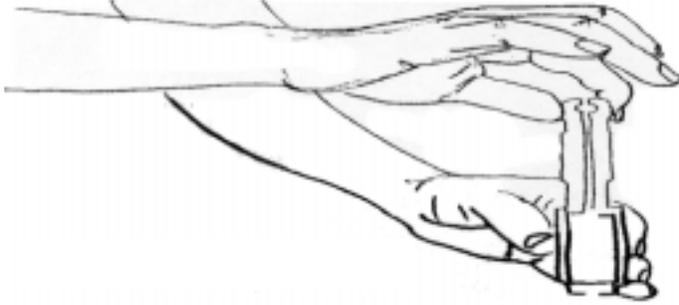


Figure 6. Illustration of the multi-digit palmar pinch coupling.

6. Three-jaw Chuck Pinch: The forearm and wrist were in a position such that the palm was down. Force was exerted between the pads of the index and middle fingers together and the pad of the thumb, through the centers of the opposing pads (Figure 7).

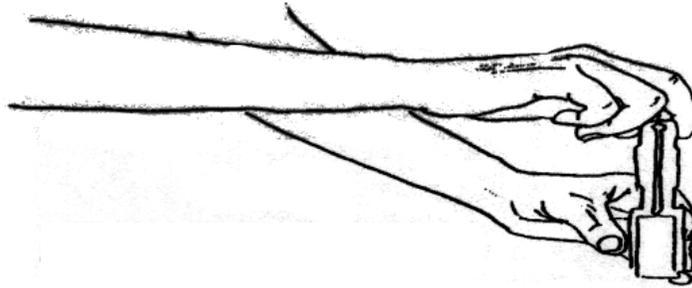


Figure 7. Illustration of the multi-digit three-jaw chuck pinch coupling.

7. Power Grasp: The wrist and forearm were in a position such that the palm was inward, toward the body. The total inner hand surface was grasping the handle that ran parallel to the knuckles. The dynamometer was held such that the participant could not read the gauge (it faced in the opposite direction). The span was set at 5.88 cm (2.35”) (Figure 8).

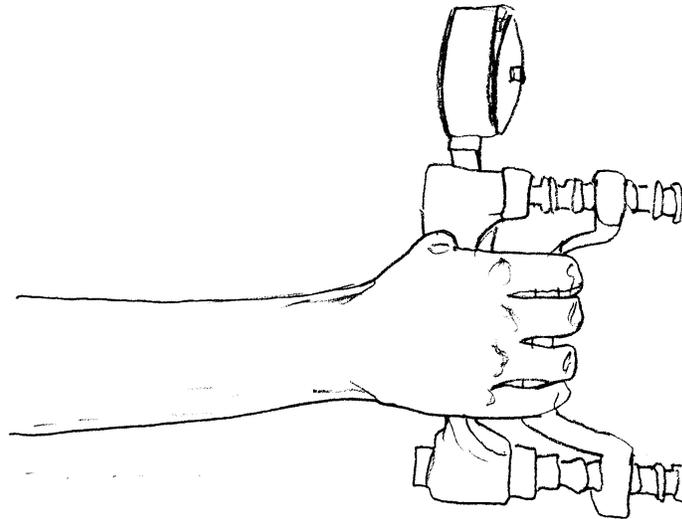


Figure 8. Illustration of the whole hand power grasp coupling.

3.2.3 Maximum Voluntary Force Measures.

Forces exerted during the trials, excluding the power grasp (grip) force, were obtained using a strain gauge force transducer. LabVIEW™ data acquisition software (National Instruments) was used to sample and store the voltages produced by the transducer. A Jamar Model 1A hand dynamometer was used to measure grip strength. Readings (in kg) from the dynamometer were obtained from a dial display, recorded manually and later converted to Newtons (N).

3.3 Participants

One hundred volunteers, between 18 and 65 years of age, were selected from the community, with an equal number of female and male participants. Participants of varying ages were used to represent a typical distribution of industrial employees. All

participants were in good health and had no history of upper limb pain or musculoskeletal injuries within the last six months.

Participants were identified in the study using a coding scheme to maintain anonymity (e.g. Subject 1 = S001). All subject information and data sheets remained confidential through the course of the study and upon completion of the data analysis. The participants were monetarily compensated for their time and participation, and were allowed to withdraw from the study at any time without penalty.

3.4 Apparatus and Materials

The experimental environment simulated seated work. An adjustable chair was used to alter the seat height and armrest heights as necessary to accommodate different sized participants. The use of the same chair and table (height at 66cm) allowed for standardization of postures between subjects.

Participant's height and weight were measured using a beam scale with built-in height pillar. Hand length, hand breadth, wrist breadth, wrist circumference, forearm circumference relaxed, forearm circumference flexed, and forearm-hand length were measured using an anthropometer and metric tape measure.

A strain gauge force transducer was used to monitor forces exerted by the finger(s) during experimental trials. The pinch gauge used resembled commercial pinch gauges, but allowed for continuous recording of force levels. The gauge consisted of two identical aluminum bars held together at their bases. Forces applied at a designated area caused a voltage change as a result of the deformation of the strain gauges that were mounted on the pinch gauge, and wired to accommodate either a half or full Wheatstone Bridge arrangement.

Prior to the recording of any data, the strain gauge force transducer was calibrated and zeroed at no load. It was previously determined that there was a nearly linear relationship between the voltages produced by the strain gauge force transducer and the forces applied to the instrument. Seven loads, with five measurements at each load, were used to determine the voltage-force relationship of the transducer. Results suggested a nearly linear relationship for the half-bridge (Figure 9) and full-bridge (Figure 10) configurations. Therefore, calibration only required the voltage reading at zero and at a

predetermined fixed weight (10 kg), and subsequent calculation of the slope and intercept. This procedure was done for each participant, to obtain the necessary calibration constants for the half- (poke, 90-degree distal pad pull, 180-degree distal pad press) and full-bridge (lateral pinch, palmar pinch, three-jaw chuck pinch) configurations. Calibration procedures were repeated after the collection of all data to verify that the voltage-force relationship had not changed. Errors in the force measurement system, resulting from environmental interference and hardware drift, were estimated as ~2%.

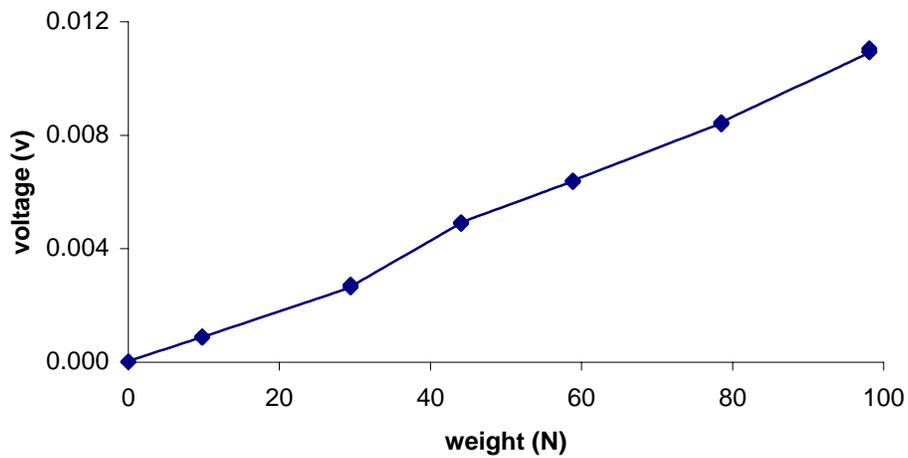


Figure 9. Relationship obtained between applied load and voltage output of strain gauge transducer (in half-bridge configuration).

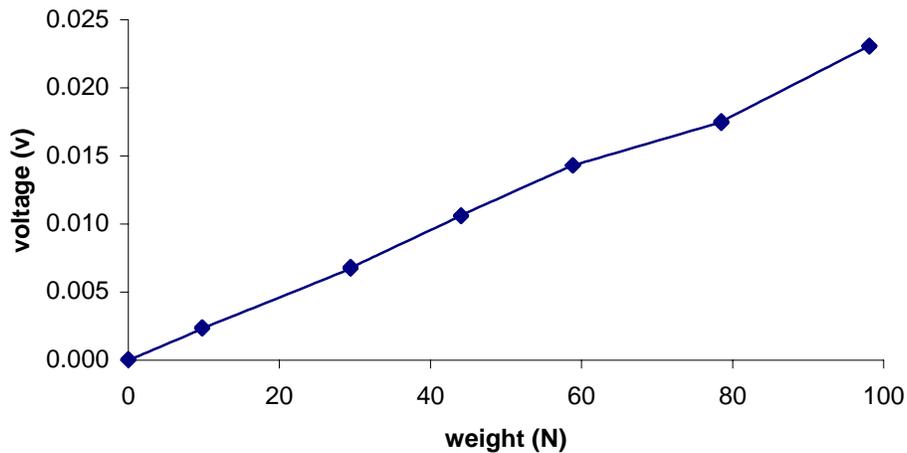


Figure 10. Relationship obtained between applied load and voltage output of strain gauge transducer (in full-bridge configuration).

LabVIEW™ data acquisition software was used to obtain output from the strain gauge force transducer. Raw voltages from the strain gauge system were A/D converted, sampled at 1024Hz, low pass filtered (2nd order Butterworth, 10Hz cutoff), and converted to units of force (N) using the calibration constants obtained earlier.

Simple grip efforts were performed using a Jamar Model 1A hand dynamometer, and the force was recorded from the analog display. Prior to the collection of any data using the dynamometer, the instrument was calibrated such that it read zero when no force was applied.

3.5 Experimental Procedures

At the onset of the experiment, participants received verbal and written information concerning the purpose, methods, and intent of the experimental procedures using a standardized set of instructions. The participants were given the opportunity to ask any questions pertaining to the study, and then required to read and sign an informed consent approved by the Virginia Polytechnic Institute and State University IRB Committee (#97-266). Participants were informed within the written instructions to notify the experimenter if they were experiencing any pain or discomfort or had been injured within

the past six months. In addition, the same issues were addressed verbally before proceeding. Upon completion of the informed consent, the participant's gender, age, dominant hand and anthropometric data were recorded.

Participants were given a set of general instructions prior to any force exertions. The experimenter read these instructions in order to maintain consistency and standardization between participants. The general instructions included a description of the procedures that were followed when the participant performed the force exertions.

Force 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 (Fess and Moran, 1981) required an upright posture with feet on the floor, the shoulder adducted, the elbow flexed at 90°, and the forearm and wrist in a neutral position. The chair supported the nondominant arm in an effort to allow the participant to concentrate on the task and focus all of their efforts on maximizing the force produced.

Past studies of hand and finger strength have concentrated on a sustained maximum exertion and commonly used the Caldwell Regimen (Caldwell et al., 1974). In contrast, subjects in the current experiment were not required to *sustain* a maximum force exertion but only to provide a peak exertion. This procedure attempted to duplicate many industrial hand-intensive tasks, in that these typically require a brief maximum or short burst of force (e.g. inserting a fastener). Participants were instructed to ramp up to their peak capacity, sustain the effort for a brief time, and then gradually ramp down. Instructions were given (see Figure 11 for an acceptable trial) to take approximately one second for each phase of the force exertions. Unacceptable trials due to inadequate ramping components or lack of a sustained maximum effort (Figure 12) were redone. An *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. Since analysis of preliminary data indicated that the actual deviations within this window were consistently below 8%, this additional acceptance criterion was not employed.

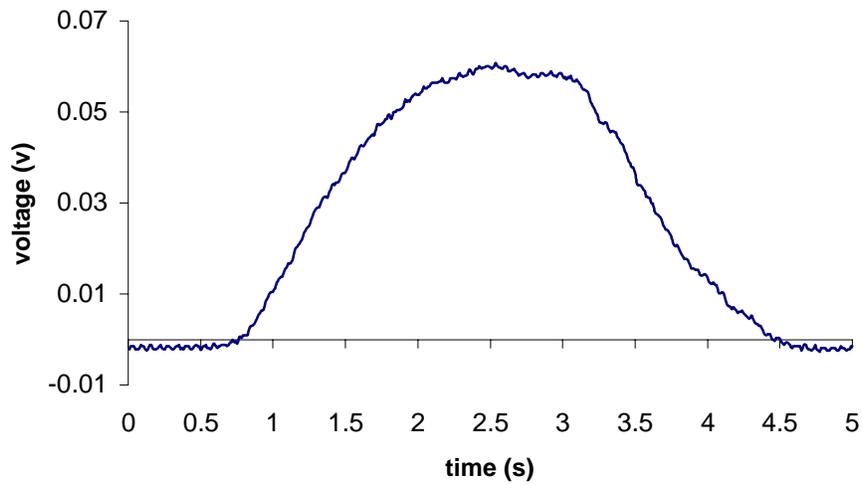


Figure 11. Example of an acceptable force exertion trial.

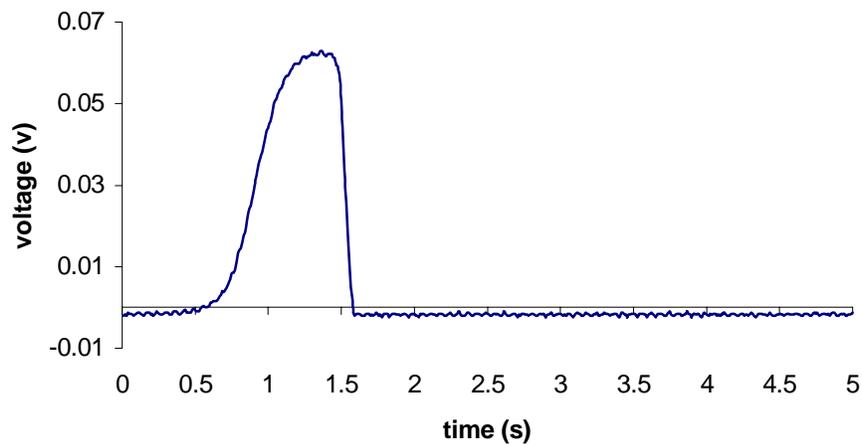


Figure 12. Example of an unacceptable force exertion trial, in which the force was released too quickly.

Immediately following the general instructions, a practice session began with the reading of a detailed description of each force exertion and a demonstration of the coupling by the experimenter. An opportunity to practice each coupling at a submaximal exertion level was given until the participant felt comfortable with the coupling and the ramping procedure. In general, one or two practice trials were sufficient for each

coupling. In an effort to provide standardized procedures, the middle grip width of 5.88 cm (2.35”) was used during all trials utilizing the Jamar Model 1A dynamometer. Moreover, a constant grip span was consistent with earlier work by Mathiowetz, et al. (1985a) and eliminated the need for additional procedures that would determine the optimal grip span for each individual.

The practice session was intended to facilitate the participant’s ability to perform the seven couplings and ramping procedure with consistent success. Efforts were made to provide enough practice for the individuals to successfully learn the procedures during the submaximal practice trials. This was important because fatigue effects were less frequent and critical during the submaximal practice trials. Repetition of trials during the maximal exertions increased the likelihood of fatigue effects and reduced motivational levels.

Prior to each trial, the experimenter identified the coupling and prepared the equipment for that specific trial. When signaled by an auditory tone (computer-generated “beep”) the participants performed the trial as previously instructed. Each trial took a total of approximately three to five seconds. Immediate feedback on the computer display allowed for identification of whether the data was acceptable, or if the trial had to be repeated. After an acceptable trial, the next condition was described, and the participant rested for a minimum of two minutes. Participants were encouraged to request more rest, or notify the experimenter, 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 centered on the overall maximum value. Within this window, the average 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.

3.6 Data Analysis Protocol

Pearson Correlation Coefficients (R) and multiple and stepwise regression models were used to examine the relationships within and among the strengths and anthropometric measures and the predictability of finger strength from grip strength and

anthropometric data. A one-sided t-test of significance using $\alpha=0.05$ was performed to determine if the R-value was significantly different from zero.

For each finger coupling, multiple linear regression models were developed that differed in terms of the predictor variables. Stepwise regression models were used to generate models with minimum subsets of predictor variables. Standard stepwise regression techniques were implemented using a probability of 0.250 to determine whether a variable should leave or enter the model. Potential predictor variables included grip strength, the nine anthropometric measures, significant two-way interactions, and principal components. In addition, multi-digit strengths were used as predictor variables for the models generated to predict single digit strengths. The models were evaluated using linear regression (measured vs. predicted strengths) and the associated adjusted coefficients of determination (R^2 -adj) and standard errors. Final derived models were chosen based on the measures of model performance (R^2 -adj and standard error), ease of use, consistency of predictor variables, and intuitiveness of regression parameters.

4. RESULTS

The experimental and data analysis protocol yielded results that are presented in this section. Peak forces (strength) were analyzed to yield summary results and evaluations of the performance of predictive models. The results were divided into five categories: anthropometric data, hand and finger strength, correlations, multivariate (MANOVA) and univariate analysis of variance (ANOVA), models for prediction of finger strength (multiple linear regression, stepwise regression and model averaging), and ridge regression.

4.1 Anthropometric Data

Anthropometric data for all subjects is summarized below (Table 1). Mean values for males were consistently higher than for females, though their ages were similar. Variability in anthropometric characteristics was relatively consistent between the two genders.

Table 1. Summary of anthropometric characteristics for all participants and classified by gender.

Measure	Total		Male		Female	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Age (yrs)	32.7	10.9	32.2	11.1	33.2	11.4
Height (cm)	166.7	12.4	173.2	7.0	160.2	13.3
Weight (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

4.2 Hand and Finger Strength

Across all subjects, strength was higher for multi-digit couplings as compared with 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. Relatively consistent coefficients of variation suggested constant strength variability relative to the mean for all of the measures. It should be noted that there seemed to be a slight increase in coefficients of variation for some of the couplings, particularly the poke, press, and pull exertions, which involved only one finger.

Table 2. Summary of strength and variability in each of the finger couplings and for simple grip across the 100 subjects.

Measure	Poke	Press	Pull	Lateral	Chuck	Palmar	Grip
Mean (N)	45.95	43.05	60.09	80.93	79.75	54.16	370.671
Standard Deviation (N)	17.8	18.43	25.24	28.15	28.96	18.84	117.729
Coeff. of Variation (%)	38.7	42.8	42.01	34.79	36.31	34.78	31.761

Considerable differences between genders for all seven exertions were found (Table 3), with males consistently generating more force. Although the values were somewhat different, the trends noted above for the standard deviations and coefficients of variation were still present when the data was separated by gender.

Table 3. Summary of strength and variability in each of the finger couplings and for simple grip classified by gender.

Gender	Measure	Poke	Press	Pull	Lateral	Chuck	Palmar	Grip
	Mean (N)	52.58	50.90	70.84	97.02	95.37	62.88	452.44
Male	Standard Deviation (N)	18.01	18.37	27.16	27.67	28.26	19.20	102.94
	Coeff. of Variation (%)	34.25	36.08	38.34	28.52	29.63	30.54	22.75
	Mean (N)	39.31	35.20	49.33	64.84	64.13	45.45	288.91
Female	Standard Deviation (N)	14.94	14.93	17.71	17.52	19.94	13.90	61.33
	Coeff. of Variation (%)	38.00	42.42	35.91	27.02	31.10	30.59	21.23

Classifying the participants by their age provided data that revealed the differences in force capabilities for various age groups. Three age groups were examined: 18-29 years, 30-39 years, and 40+ years. In the population studied, strength for the seven exertions (Table 4) indicated a slight increasing trend between age and strength for age groups typical of a working population (20-65 years of age). Standard deviations were consistent between age groups but the coefficients of variation were lowest for the 30-39 year age group.

Table 4. Summary of strength and variability in each of the finger couplings and for simple grip classified by age.

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

4.3 Correlations

Correlations (R) within and between the finger and grip strengths and anthropometric measures (Table 5) were dependent on the specific variables, although some consistent patterns were observed. In contrast to the finger exertions, simple grip strength showed relatively higher correlations (0.51-0.74) with the anthropometric measures, excluding weight. In general, multi-digit strengths were more highly correlated with the anthropometric measures of the hand and wrist (0.37-0.67) as compared to that of the single digit strengths (0.31-0.52).

Table 5. Pearson's Correlation Matrix (R) for Strength Measures and Anthropometric Measurements

Task	poke	press	pull	lateral	chuck	palmar	grip
Grip Force	<i>.57</i>	<i>.57</i>	<i>.61</i>	<i>.70</i>	<i>.76</i>	<i>.65</i>	—
Height	.26	.26	.29	<i>.40</i>	<i>.41</i>	<i>.33</i>	<i>.51</i>
Weight	<i>.33</i>	.24	<i>.32</i>	<i>.37</i>	.22	<i>.33</i>	<i>.29</i>
Hand Length	<i>.32</i>	<i>.33</i>	<i>.36</i>	<i>.48</i>	<i>.52</i>	<i>.42</i>	<i>.71</i>
Hand Breadth	<i>.45</i>	<i>.45</i>	<i>.52</i>	<i>.63</i>	<i>.60</i>	<i>.51</i>	<i>.72</i>
Wrist Breadth	<i>.49</i>	<i>.46</i>	<i>.52</i>	<i>.67</i>	<i>.60</i>	<i>.55</i>	<i>.74</i>
Wrist Circum.	<i>.37</i>	<i>.36</i>	<i>.44</i>	<i>.60</i>	<i>.48</i>	<i>.51</i>	<i>.66</i>
F-H Length	<i>.34</i>	<i>.33</i>	<i>.31</i>	<i>.54</i>	<i>.47</i>	<i>.37</i>	<i>.55</i>
F Circ Relaxed	<i>.37</i>	<i>.31</i>	<i>.36</i>	<i>.51</i>	<i>.41</i>	<i>.47</i>	<i>.58</i>
F Circ Flexed	<i>.41</i>	<i>.36</i>	<i>.43</i>	<i>.54</i>	<i>.47</i>	<i>.52</i>	<i>.62</i>

**bold and italics* represents significance at $p \leq 0.05$

Correlations within and between the anthropometric variables (Table 6) were dependent on the human body segments and the level of similarities in the measures. Correlation values were high, with the hand and arm anthropometric measures more highly correlated (0.51 – 0.98) with each other as compared to correlation values with height (0.35 – 0.60) and weight (0.29 – 0.73). Highest correlation values were found between anthropometric values that measured the same body segment. For example, forearm circumferences flexed and relaxed were highly correlated at 0.98 due to the similarity in the two measurements.

Table 6. Pearson's Correlation Matrix (R) for Anthropometric Measurements

R-values	Weight	Hand Length	Hand Breadth	Wrist Breadth	Wrist Circ	F-H Length	F Circ Relaxed	F Circ Flexed
Height	-0.08	0.60	0.47	0.52	0.42	0.58	0.36	0.35
Weight		0.29	0.44	0.45	0.58	0.38	0.72	0.73
H Length			0.76	0.77	0.67	0.81	0.56	0.56
H Breadth				0.87	0.77	0.70	0.64	0.65
W Breadth					0.86	0.74	0.67	0.69
W Circ						0.62	0.78	0.81
F-H Length							0.54	0.51
F Circ Relax								0.98

**bold and italics* represents significance at $p \leq 0.05$

Lastly, correlation coefficients between single and multi-digit strengths (Table 7) were calculated. In general, multi-digit strengths were moderately correlated with single digit strengths (0.66 – 0.77). Correlation values were consistent for the single digit strengths across all multi-digit strengths with the highest correlations (0.73 – 0.77) corresponding to the pull and lowest correlations (0.66 – 0.69) corresponding to the poke.

Table 7. Pearson's Correlation Matrix (R) for Single Digit Force Exertions versus Multi-digit Forces.

	lateral	chuck	palmar
poke	0.66	0.66	0.69
press	0.72	0.72	0.71
pull	0.73	0.74	0.77

**bold and italics* represents significance at $p \leq 0.05$

4.4 Multivariate (MANOVA) and Univariate Analysis of Variance (ANOVA)

A multivariate analysis of variance was performed to evaluate any age, gender, or interaction effects on the set of dependent variables (single and multi-digit coupling strengths). Using the Wilks' Lambda test and an alpha significance level of 0.1, the

gender effect ($p=0.004$) and the (gender x age) interaction effect ($p=0.0743$) were significant. Subsequently, 2x3 repeated measures univariate analyses of variance were performed for each dependent variable (single and multi-digit coupling strength), with a critical alpha level of 0.1.

The gender effect was found to be significant for a number of the dependent variables, including the poke ($p=0.0284$), lateral pinch ($p=0.0006$), three-jaw chuck pinch ($p=0.0009$), and palmar pinch ($p=0.0071$). This main effect of gender was seen as consistently larger strength in males for all couplings (Figure 13). In addition, average female finger strength, relative to males, was somewhat consistent across couplings at approximately 70%. Although significant within the MANOVA results, the (gender x age) effect was not found to be significant for any of the dependent measures separately. Consistent with the findings of the MANOVA, the age effect was also found to be not significant for any of the dependent variables.

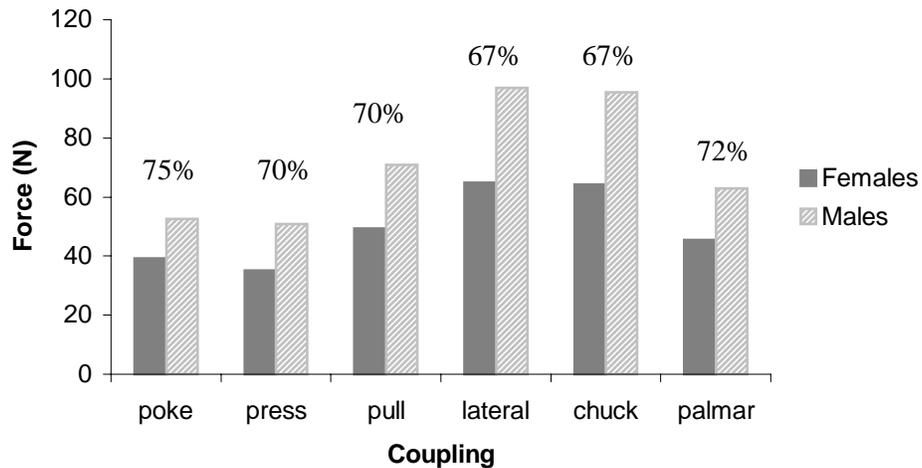


Figure 13. Average strengths for females and males for each coupling. Average female strengths are given as a percentage of the male values.

Although not statistically significant, there were trends indicating differences in strength in the older participants (Figure 14). Across five age categories, created such

that the sample sizes in each group were approximately equal (~20 participants), a slight increase in average strength was apparent in older participants.

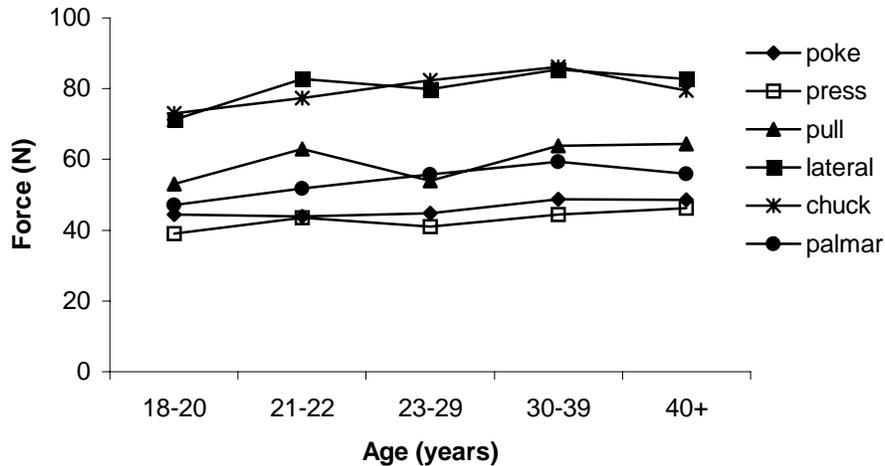


Figure 14. Average strength for each coupling across five age classifications.

4.5 Models for Prediction of Finger Strength

Models for predicting finger strength were obtained using several approaches. Using stepwise, principle components, and ridge regression, as well as model averaging, models were generated using combinations of anthropometric and strength measures to predict finger strength. Accuracy of the derived models was determined from the adjusted coefficient of determination (R^2 -adj) that provided an overall measure of performance adjusted for the number of model parameters. The standard error of the regression model was also used to qualify prediction error. Both measures facilitated comparisons between models.

Only linear terms were considered for all regression analyses. Nonlinear terms were excluded because simple regression analyses relating each dependent variable with each independent variable showed only linear relationships. None of the relationships exhibited any substantial deviation from linearity. Figure 15 provides an illustration of a typical linear relationship.

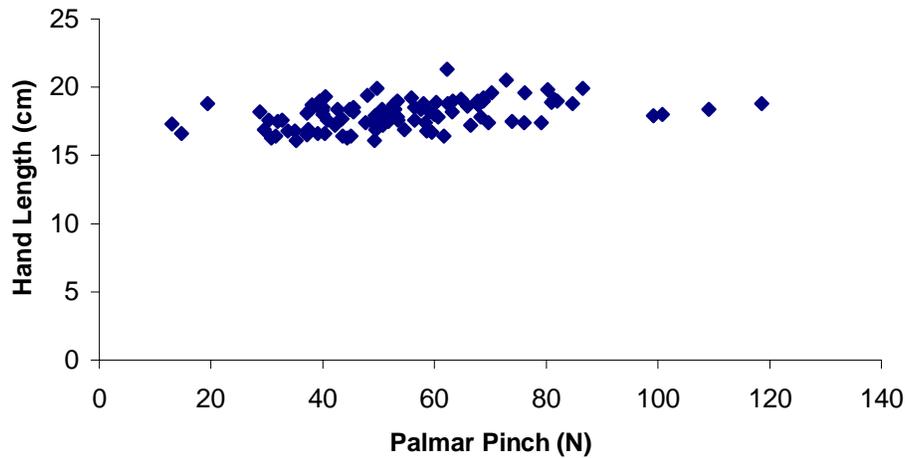


Figure 15. Relationship between hand length and palmar pinch strength. A linear relationship, as seen here, was typical for all dependent and independent variable combinations.

4.5.1 Multiple Linear and Stepwise Regression

Several sets of independent variables were considered as predictor variables for the strengths in each coupling. The overall goal was to obtain a model that was statistically significant, accurate and contained variables that were easily obtainable. For comparison, three different regression analysis methods were used: multiple linear regression, stepwise regression and model averaging. Multiple linear regression was used to generate baseline models containing all of the independent variables as predictor variables. The stepwise method started out with no variables in the model and then used forward selection and backward elimination to add and remove variables to generate a model with minimal predictor variables and reliable predictability (Neter, Kutner, Nachtsheim, and Wasserman, 1996). Model averaging considered all possible stepwise regression models and combined the three most probable models to create the “best” model.

The first set of predictor variables considered included grip strength and all anthropometric measures. The R^2 -adj values ranged from 0.33 – 0.58 (Figure 16). Values for the single digit strengths were consistently lower than those of the multi-digit

strengths. Standard errors ranged from 13.87N – 18.98N (Figure 17) with the largest values corresponding to the 90-degree distal pad pull, lateral pinch, and three-jaw chuck pinch.

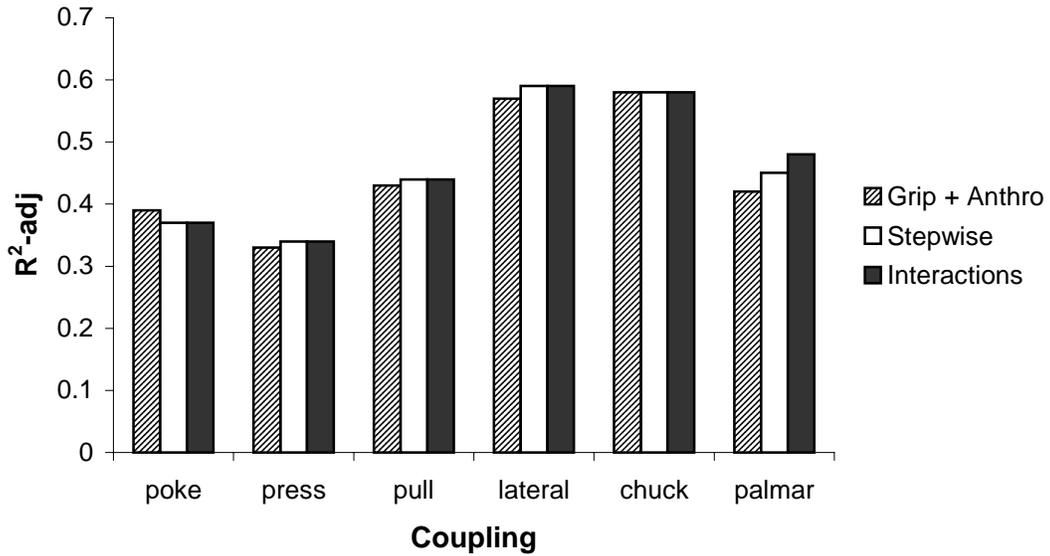


Figure 16. Comparison of regression models using all predictor variables and significant interactions.

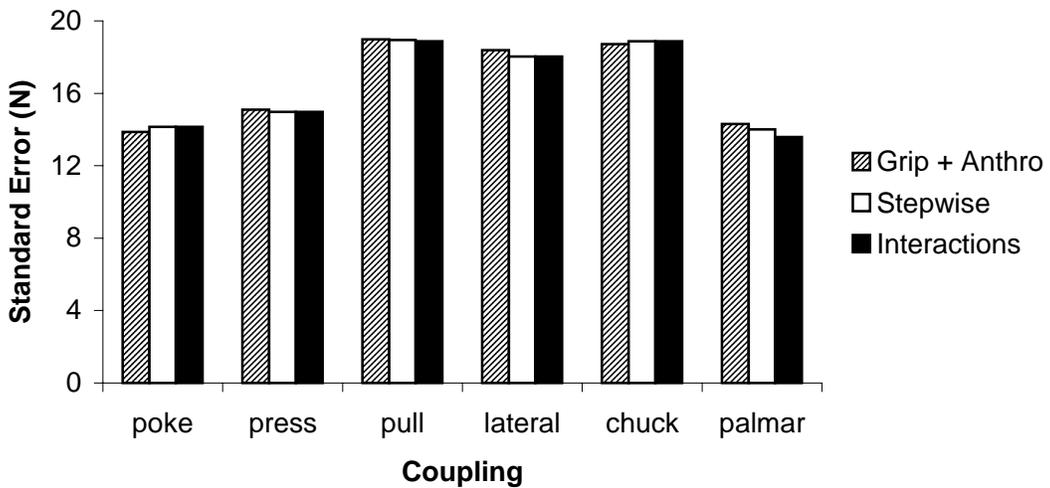


Figure 17. Comparison of standard errors for regression models using all predictor variables and significant interactions.

Stepwise regression analysis was used to generate models that reduced the number of predictor variables. The predictor variables obtained from stepwise procedures are given below for each coupling.

- **Poke:** Grip, Weight, Hand Length, Forearm-Hand Length
- **Press:** Grip, Hand Length, Hand Breadth
- **Pull:** Grip, Height, Weight, Hand Length, Hand Breadth, Forearm Circumference Relaxed, Forearm Circumference Flexed
- **Lateral:** Grip, Hand Length, Wrist Breadth, Forearm-Hand Length
- **Chuck:** Grip, Hand Breadth, Wrist Circumference
- **Palmar:** Grip, Weight, Hand Length, Wrist Breadth

The R^2 -adj values associated with each of these models ranged from 0.33 to 0.59 (Figure 16). Higher coefficients of determination were found for the multi-digit couplings, however, performance of these models was not substantially different from the models that included all predictor variables. R^2 -adj values, however, were occasionally larger when using the stepwise models, because of the reduced set of parameters. Standard errors ranged from 14.01N – 18.95N which were comparable to those of the multiple regression models.

Two-way interactions of the anthropometric measures were also considered as predictor variables. An analysis of variance was used to determine the significant two-way interactions using an alpha significance level of 0.1. Stepwise regression analysis was repeated using grip, anthropometric measures, and the significant two-way interactions as predictor variables. As previously noted for the other regression analyses, better model performance occurred for the multi-digit couplings as compared to the single digit couplings (Figure 16). Models using the significant two-way interactions were comparable to both previous approaches in R^2 -adj values and standard errors.

Additional analyses sought to generate models with improved ability to predict single digit strength. Stepwise regression models were generated to predict single digit coupling strength using only the multi-digit coupling strengths as the set of predictor variables. The R^2 -adj values ranged from 0.52 – 0.65 with standard errors of 11.95N – 15.23N. The predictor variables included in each model are provided below:

- **Poke:** lateral, palmar
- **Press:** lateral, chuck, palmar
- **Pull:** lateral, chuck, palmar

Furthermore, stepwise procedures were repeated using a set of predictor variables consisting of the multi-digit couplings, grip strength, and anthropometric measures. Lastly, significant two-way interactions were added to this set of predictor variables and stepwise regression models generated. Comparison of model performance (R^2 -adj and standard error) for the regression analyses showed no substantial differences between approaches (Figure 18 and Figure 19).

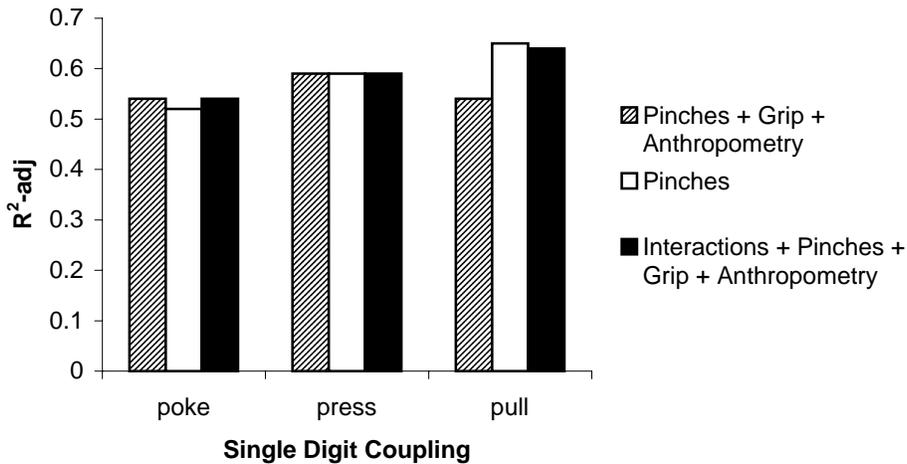


Figure 18. R^2 -adj values corresponding to estimations of single digit strength from pinch strength.

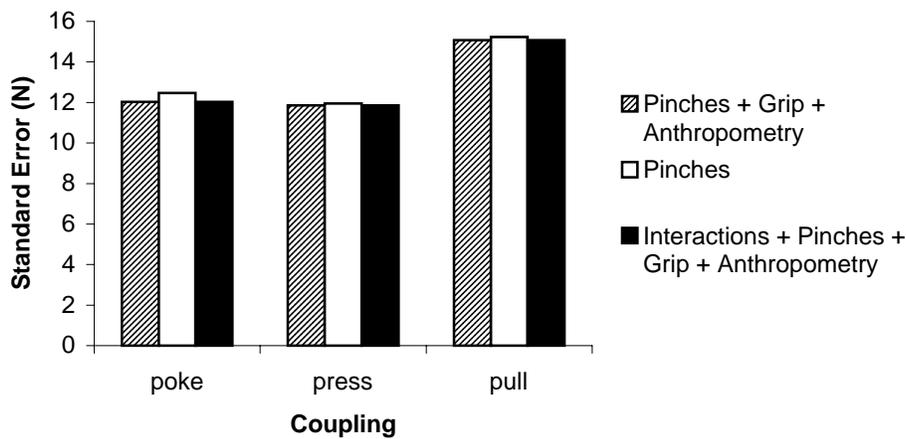


Figure 19. Standard error values corresponding to estimations of single digit strength from pinch strength.

Beyond performing stepwise regression to predict the single digit strength from the multi-digit strength, multiple linear regression was used to predict single digit strength from just one multi-digit strength. By reducing the number of multi-digit strengths that were required to predict the single digit strengths, models were generated that would be easy to implement and utilize. In an effort to increase model performance, grip strength was added to these models as a predictor variable. High predictability in either situation would allow for the use of a limited set of easily obtainable predictor variables.

The models predicting single digit strength from one multi-digit strength measure were less accurate (0.43 – 0.59) than the stepwise regression models that considered all three multi-digit strengths as predictor variables (0.52 – 0.65). Furthermore, the addition of grip strength as a predictor variable made no significant difference in model performance (0.44 – 0.60). Using R^2 -adj values (Table 8) for comparison, none of the multi-digit strengths consistently provided more accurate predictions of the single digit strengths.

Table 8. R^2 -adj values for multiple regression models predicting single finger strength from one multi-digit strength and grip strength.

	lateral	lateral + grip	chuck	chuck + grip	palmar	palmar + grip
poke	.43	.45	.43	.44	.47	.49
press	.52	.52	.51	.51	.49	.51
pull	.52	.54	.54	.54	.59	.60

Principal components analysis was used to create new predictor variables that were orthogonal to each other. Although this type of analysis minimized the affects of multicollinearity, it did not increase the level of predictability of the dependent variables. Stepwise regression models were generated from grip strength and the new independent variables. Three different models were generated: multiple linear regression using all of the components and grip strength, multiple linear regression using the five components that accounted for most of the variance (~95%) and grip strength, and stepwise regression using all components and grip strength. Model performance (Figure 20 and Figure 21) was consistently better for models predicting multi-digit strengths. Overall the stepwise regression models produced the highest R^2 -adj values (0.36 – 0.60) and the lowest standard errors (13.63N – 18.93N). The performance of the regression models generated from grip strength and the five best orthogonal variables (R^2 -adj: 0.31 – 0.57; standard error: 16.09N – 24.21N) was worse than those predicted from grip strength and all nine orthogonal variables (R^2 -adj: 0.33 – 0.58; standard error: 14.97N – 21.70N).

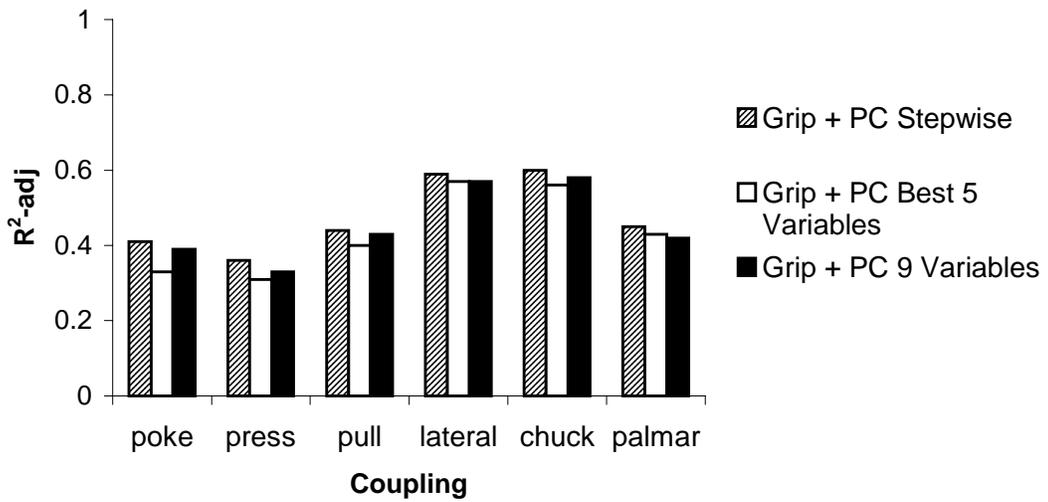


Figure 20. Comparison of R^2 -adj associated with regression models using principal components as predictor variables.

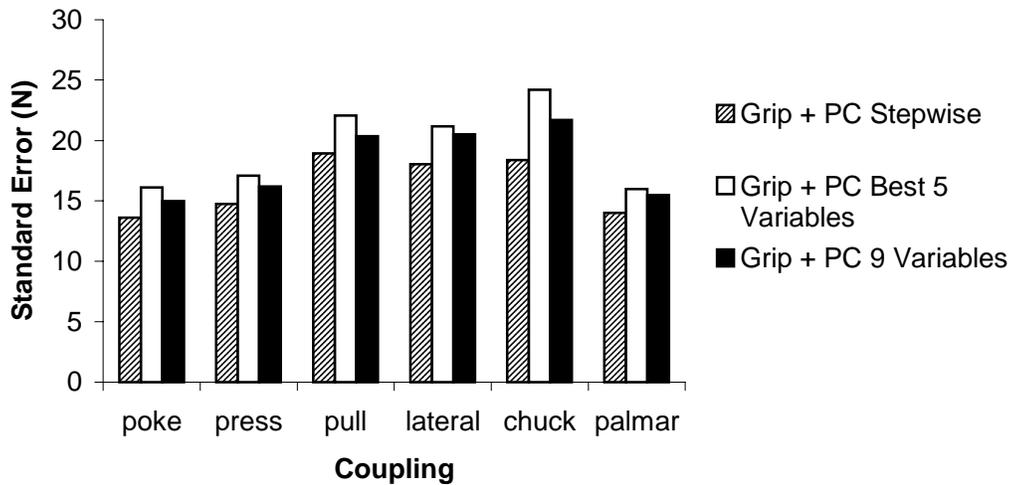


Figure 21. Comparison of standard errors associated with regression models using principal components as predictor variables.

As shown earlier (Table 2), males have a greater strength capability, relative to females, when performing exertions using the hand and fingers. To examine a potential gender difference, predictability of finger strength was examined separately for each gender, using multiple linear and stepwise regression. Models generated separately for each gender had R^2 -adj values (multiple linear: 0.09 – 0.51; stepwise: 0.19 – 0.49) lower (Figure 22) than those using the entire data set and standard errors (13.1N – 22.7N) of the same magnitude (Figure 23). However, performance was better for females with higher R^2 -adj values and smaller standard errors.

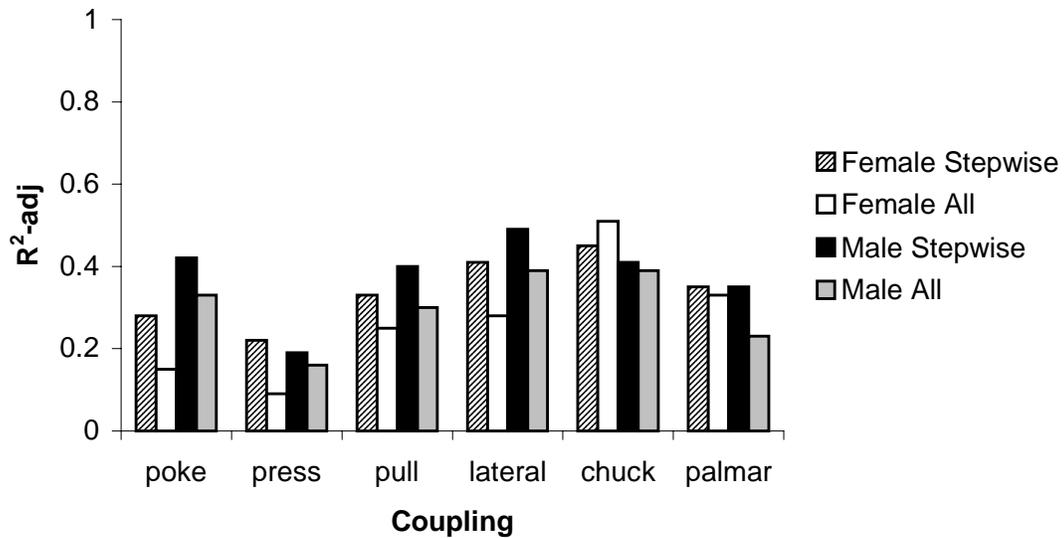


Figure 22. R^2 -adj for regression models considering gender categorizations.

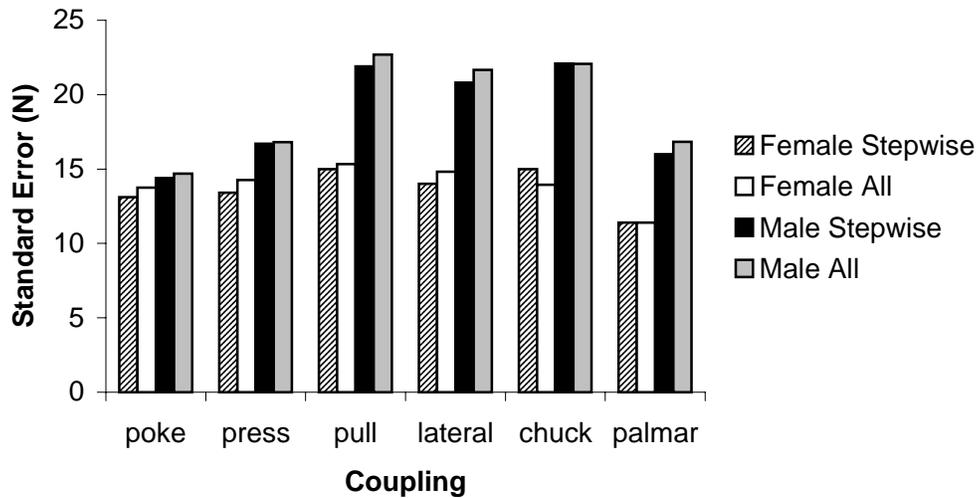


Figure 23. Standard errors for regression models considering gender categorizations.

4.5.2 Model Averaging

Model averaging is a procedure implemented when stepwise regression is needed for a large number of predictor of variables. Instead of considering only the “best” regression model, model averaging considered a predetermined number of “good” models (three for this research) and used them to create a composite model. The model building procedure is described below (Raftery, Madigan, and Hoeting, 1997):

Step 1 – the Bayesian variable selection algorithm was used to identify important individual variables.

Step 2 – analysis of variance identified important second order terms.

Step 3 – all important second order terms and individual terms that were significant when considered by themselves or included in an interaction were considered.

Step 4 – Bayesian model averaging computed model posterior probabilities.

Step 5 – a composite model was created from the three most likely models.

Model averaging was used to generate predictive models for the single digit strengths. The models created from this procedure included predictor variables from the set of grip strength, anthropometric measures, multi-digit strengths and significant two-way

interactions. Comparison of R^2 -adj values and standard errors, respectively, from these models (0.51 - 0.63; 12.08N – 15.33N) with those of the models generated from the stepwise regression using grip strength, anthropometric measures, and multi-digit strengths (0.52 - 0.65; 14.14N – 18.95N) showed no substantial differences. However, the variables chosen to be included within the models were dissimilar. The models generated from this procedure included the following predictor variables:

- **Poke:** lateral, palmar, wrist breadth, wrist circumference
- **Press:** lateral, palmar, hand breadth, wrist circumference
- **Pull:** lateral, three-jaw chuck, palmar, palmar x hand breadth

Note that the lateral and palmar pinches were predictor variables in all of the models.

4.6 Ridge Regression

Ridge regression modified the method of least squares to allow for biased estimators of the regression coefficients. This analysis 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. However, since ridge regression did not improve the predictability of the dependent measures, further investigation using this type of analysis was not pursued.

5. DISCUSSION

Hand intensive tasks and chronic and acute injuries of the upper limbs are common in industry. Frequent forceful motions are included in the list of risk factors for these types of injuries. Many of these problems could be avoided if hand tools and hand intensive workstations were designed by integrating an understanding of human capabilities. Such design is hampered, however, by incomplete knowledge concerning the force capabilities of the hand and fingers. Although a number of studies have examined grip strength, and a good basis has been established for pinch strength, little data is available regarding the force capabilities (strength) of single digits, particularly the index finger.

This research was motivated by the need to enhance existing data for grip and pinch strength, as well as to provide data on single digit strength using the index finger. In addition, the determination of finger force capabilities and requirements is an integral part of an effective design process. The prediction of finger strength from easily obtainable measures provides pertinent and necessary data without the challenges of collecting force data during tasks and potentially disrupting the individual. The hope is to design hand tools and hand intensive workstations so that an individual must apply a minimum amount of force and minimize the risk of injury.

Peak forces were collected to determine grip strength, pinch strength for three commonly used couplings (lateral pinch, three-jaw chuck pinch, and palmar pinch), and strength during three frequently used single digit (index finger) couplings (poke, 180-degree distal pad press, and 90-degree distal pad pull). Many hand intensive industrial tasks replicate one or more of these couplings. Therefore, a database describing these strengths encompasses most tasks and is useful for many designs. Regression models were generated to provide a means for predicting finger strength for specific individuals or groups, whereas the database provides estimates for the entire working population. Interpretations of the results are included in this discussion section.

5.1 Anthropometric Data

Anthropometric data was collected and presented for the entire group of 100 participants, as well as for the gender classifications of males and females. The data set represented a diverse working population (18-65 year olds) with a range of values for all anthropometric measures. Variations across subjects for each anthropometric measure illustrated large physical differences between individuals. The gender division demonstrated that all measures were greater for males as compared to females, however, standard deviations were similar between the two gender categories.

5.2 Hand and Finger Strength

Average strength was consistently larger for multi-digit compared to single digit couplings. Grip strength was the largest of all of the strength values measured. Strength exhibited with each coupling differed due to changes in the direction of the force and the contact surfaces utilized. Larger forces were produced as additional digits were employed and as the contact area increased between the digits and the gauge. Although standard deviations increased proportional to the increase in strength magnitude, the 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. This may be explained by differences in posture maintained during these exertions. These couplings may also be intrinsically more variable between subjects. It was also possible that the recruitment of more muscle groups and multiple digits resulted in both higher strength levels and lower inter-subject variability.

Peak forces produced by males (50.90N – 97.02N) were consistently larger than those produced by female participants (35.20N – 64.84N). The coefficients of variation were similar (22.75 – 38.34 for males as compared to 21.23 – 42.42 for females) which indicated a consistent variation when adjusting for the magnitude of the mean between genders. Small differences in the coefficients of variation may be a reflection of the participant samples used within the study. Previous research and common practice have shown that in general, males are stronger than females. The magnitude of the difference found here, with females consistently at ~70% of males across couplings, was

comparable to gender differences found in other studies (Berg et al., 1988; Roebuck, Kroemer, and Thomson, 1975; Webb Associates, 1978).

A comparison of the strength in the three age groups did not reveal significant differences for any of the finger couplings. Differences within couplings ranged from ~1% to ~9% (1N – 7N). In addition, the coefficients of variation were similar with slightly less variability in the 30-39 year old age group (23.26 – 38.08 as compared to 31.83 – 44.58 for the 18-29 age group and 33.32 – 47.80 for the 40+ age group). 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. Some indications that strength may actually increase with age were found (Figure 14), but the age related differences were nonetheless minor.

While no data on single finger strength could be found in the literature, several existing studies allow for comparison of multi-digit strength with the present work. In comparison to the results of Mathiowetz et al. (1985a) and Imrhan (1989), the present data are similar in terms of both means and variability (Table 9). 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.

Table 9. 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)	
	Males (n=50)	Females (n=50)	Males (n=288)	Females (n=295)	Males (n=40)	Females (n=30)
Average Force						
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)

5.3 Correlations

Correlations between and among the grip and finger strengths and anthropometric measures revealed substantial multicollinearity. Each correlation coefficient provided an indication of the relationship between two variables. Correlations among anthropometric measures were typically high, as has been demonstrated in earlier research (Cheverud, Gordon, Walker, Jacquish, Kohn, Moore, and Yamashita, 1990; Kroemer, Kroemer, and Kroemer-Elbert, 1990; Webb Associates, 1978). Only moderate correlations were found between finger strength and the anthropometric measures of the hand and arm. These findings were consistent with correlation values determined by Laubach and McConville (1969) and Chaffin, Herrin, Keyserling, and Foulke (1977) where anthropometric measures were used to predict static strength. Imrhan (1989) found even lower correlation values between multi-digit strength and the anthropometric measures: height, weight, hand length and hand breadth. However, large and consistent correlations between single digit strength and multi-digit strength indicated that the inclusion of strength measures as predictor variables in regression models should be beneficial, similarly demonstrated by Stobbe (1982).

Identifying the relationship among the anthropometric measures also provided a means for determining which quantities might be unnecessary due to a redundancy in measurements (for example, hand length and forearm-hand length). Based on high correlation values and redundancy, hand length and forearm circumference (relaxed) may have been eliminated from the set of anthropometric predictor variables.

5.4 Age and Gender Differences in Finger Strength

Finger strengths as a whole differed significantly depending on the gender and age of the participant. The interaction effect was not found to be significant in univariate analysis for any of the dependent variables. Therefore, this effect may have been significant based on the entire set of dependent variables, but for each coupling this effect was not evident. A gender effect was significant for four of the six couplings: poke, lateral pinch, three-jaw chuck pinch, and palmar pinch. This means that for these exertions, as well as the remaining two that were not significantly different, a consistent gender difference in strength was found (Figure 13). During the design process for tasks

that require finger exertions, these results suggest that the gender of the intended end user must be considered.

In contrast to gender, the main effect of age was not significant. Although the age effect was not found to be significant in the multivariate analysis of variance or the univariate analysis of variance, there did seem to be the indication of a possible trend in the data (Figure 14). As individuals age, strength may increase slightly with a possible small decline over 40 years of age. This trend needs to be clarified by collecting more data from participants over the age of 30 years 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. Additional changes in strength may be due to any number of environmental and developmental factors. The present social culture has seen an increase in health consciousness, and this phenomenon may partially account for the increase of strength in the 30-39 year old age group. Unfortunately the aging process cannot be completely reversed so some eventual decline in strength was to be expected. Compared to the declines in overall strength of approximately 5 – 20% (Roebuck et al., 1975), the decline for the hand and fingers was found to be minimal. Perhaps shifting older employees to hand intensive tasks from heavy manual labor tasks would reduce injuries and maintain productivity of the employees. Conversely, it may not be imperative that the age of the end user be considered.

5.5 Regression

A large set of possible predictor variables would be impractical to use by a practitioner, because of the need for extensive measurement. One of the purposes of this research was to create prediction models from a limited set of easily obtainable measures.

5.5.1 Multiple Linear and Stepwise Regression

Multiple linear regression models included all pertinent predictor variables for the desired situation. They were used primarily as comparative tools for subsequent regression models using reduced numbers of predictor variables. Stepwise regression models were used to obtain predictive models that included minimal numbers of predictor variables but also provided high predictive accuracy. As the intention 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 provide 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).

General observations regarding the formulation of various regression models to predict finger strengths eliminated many of the potential models. Regression models were analyzed using data that was classified into two gender categories but R^2 -adj values (0.19 – 0.49) for these models were significantly lower and standard errors higher (11.4N – 22.7N) than those where gender was not considered. The decrease in model performance indicated a similar level of predictability for both genders. In the absence of a gender classification, the increased number of data points and the increased range of the data provided a more accurate representation of the data set. Therefore, using a subset of the data, accounting for gender differences, to predict a force was not pursued any further.

In addition, inclusion of significant two-way interactions provided no benefit during stepwise analyses (R^2 -adj: 0.34 – 0.59; standard error: 13.59N – 18.88N), performing comparably to the stepwise regression analyses using only grip strength and anthropometry (R^2 -adj: 0.34 – 0.59; standard error: 13.87N – 18.98N) as predictor variables. Furthermore, the inclusion of two-way interactions provided no additional accuracy in models that also included pinches as predictor variables for single digit forces. Since the two-way interactions are harder to compute and interpret, models containing only the actual measures were considered.

Principal components regression was used in an attempt to minimize the affects of multicollinearity. Although the variables generated were orthogonal, they had no obvious physical interpretation and implementation would require additional calculations prior to utilizing the regression models. Models obtained from principal components regression provided a slight increase in predictability (R^2 -adj: 0.36 - 0.60), when compared to the stepwise regression models using grip and anthropometry (R^2 -adj: 0.33 –

0.58), but at the expense of simplicity. Therefore, models based on principal components were not considered.

Prediction of single finger strength could not be done with high accuracy when only grip strength and anthropometric measures were utilized as possible predictor variables (R^2 -adj: 0.33 – 0.43; standard error: 13.87N – 18.98N). The prediction of single digit strength from multi-digit strength, however, showed a marked improvement (R^2 -adj: 0.52 – 0.65; standard error: 11.95N – 15.23N). Stepwise regression models based solely on multi-digit forces as predictor variables had R^2 -adj and standard error values comparable to the models that included grip strength and anthropometry as well as the multi-digit strength (R^2 -adj: 0.54 – 0.64; standard error: 11.86N – 15.07N). Thus, use of multi-digit strength alone is an alternative to the use of anthropometry and grip strength when predicting single digit strength, and requires fewer measurements.

The prediction of the multi-digit strength was relatively accurate (R^2 -adj: 0.42 – 0.58; standard error: 14.01N – 18.88N) when only grip strength and anthropometric measures were included in the set of possible predictor variables. This was consistent with results presented by Hallbeck et al. (1989) that only considered hand length, hand breadth and finger length. As previously stated, attempts to manipulate the predictor variables to improve predictability were unsuccessful. Using principal components and two-way interactions did not significantly improve the accuracy of the regression models so the original regression models based on grip strength and anthropometry were preferred. Alternatively, provided the practitioner has a pinch gauge, multi-digit strengths may be easily obtained by direct measurement.

5.5.2 Model Averaging

Model averaging is a relatively new statistical procedure that uses a relatively complex multi-step procedure in order to generate a regression model. Although the procedures considered all possible models for predicting single digit strengths, and even considered significant two-way interactions (R^2 -adj: 0.51 – 0.63), the R^2 -adj values were not significantly different from those obtained using simple stepwise regression techniques (R^2 -adj: 0.54 – 0.59). Due to the complexity of the procedures, simple stepwise regression models were preferred.

5.6 Ridge Regression

Ridge regression analysis was performed to eliminate the negative parameters in the regression models that arose due to the affects of multicollinearity, not improve predictability. Negative parameters do not have practical physical interpretations when discussing sizes of body parts. Anthropometric measures are positive values that intuitively result in larger strength magnitudes when increased. Negative parameters suggested that an increase in the anthropometric measure would result in a reduction of strength. Although mathematically the equations were valid, this consequence was counterintuitive. Since it was not imperative to eliminate the negative parameters, the existing models were as useful as the models generated using ridge regression that still contained negative parameters. Therefore, ridge regression was not investigated any further since it did not seem to provide any obvious benefits.

5.7 Derived Regression Models

Specific regression models were selected based on predictive accuracy that was determined by large R^2 -adj values and minimal standard errors. In addition, minimal sets of easy to measure predictor variables were necessary. Secondary considerations were given to consistency of predictor variables between models and intuitive physical interpretations. Models are presented below for the prediction of single and multi-digit strengths that attempted to meet these goals. Table 10 provides the R^2 -adj and standard error values for the given models.

$$\mathbf{Poke} = 6.66 - 0.155\text{LATERAL} + 0.0976\text{CHUCK} - 0.350\text{PALMAR}$$

$$\mathbf{Press} = -0.21 + 0.203\text{LATERAL} + 0.158\text{CHUCK} + 0.264\text{PALMAR}$$

$$\mathbf{Pull} = -1.81 + 0.188\text{LATERAL} + 0.199\text{CHUCK} + 0.570\text{PALMAR}$$

$$\mathbf{Lateral} = 22.3704 + 0.1441\text{GRIP} - 14.0993\text{HL} + 19.1520\text{WRB} + 3.3257\text{FHL}$$

$$\mathbf{Chuck} = -16.9309 + 0.1710\text{GRIP} + 9.6719\text{HB} - 2.8904\text{WRCIRC}$$

$$\mathbf{Palmar} = 39.3142 + 0.0991\text{GRIP} + 0.1140\text{WEIGHT} - 4.0699\text{HL} + 7.8355\text{WRB}$$

- 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)
- WEIGHT: Lightly Clothed Weight (kg)

Table 10. Measures of accuracy (R^2 -adj and standard error) for selected models to predict single and multi-digit strength.

Coupling	R^2 -adj	Standard Error (N)
poke	0.51	12.46
180-degree distal pad press	0.58	11.95
90-degree distal pad pull	0.64	15.23
lateral pinch	0.59	18.04
three-jaw chuck pinch	0.58	18.88
palmar pinch	0.45	14.01

These regression models were generated to predict finger forces from easily obtainable multi-digit pinch strengths, grip strength, and anthropometric measures. Although Schmidt and Toews (1970) were able to predict grip strength from easily obtainable measures (age, weight, and height) with a predictive accuracy of 95%, the models derived in this study were only moderately accurate but provide a means for providing a basic indication of an individual’s finger force capabilities.

5.8 Applications

The couplings chosen for this study formed a basis for many of the hand intensive exertions required within industrial and other work settings. Given the prevalence of upper limb musculoskeletal disorders and ongoing efforts to design tools and workstations that minimize the risk of injury, accounting for human capabilities is an

integral portion of the design process. Part of the design process includes determining the amount of force required when performing an action (e.g., pushing a button, sliding a lever, etc.). In order to minimize injury, force requirements should be within “safe” limits for the intended user population. These guidelines are determined for specific exertions and to minimize the occurrence of musculoskeletal and cumulative trauma disorders (e.g., force requirement should be less than 15% of individual’s strength). The findings of this study provided a guide for the designer to use when determining the forces required in order to complete a task requiring the use of the hand or fingers. Minimizing the risk of injury requires the appropriate integration of design recommendations and human capability data.

In addition to design, these models can be used to determine the likelihood that an individual can perform a hand intensive task or set of tasks without injuring themselves due to excessive force exertions. Finger strength of an individual can be determined using the models and then a percentage can be calculated and compared to safe force requirement guidelines. Otherwise, they can aid in matching people with existing jobs by determining the requirements of the job and comparing them to the capabilities of the person.

Lastly, knowledge of human capabilities is useful in the determination of injury and progress during rehabilitation. In order to determine decrements in strength (or increases during rehabilitation) it is necessary to know what is “normal”. The database created provides this data for a representative working population that can be compared with individuals from a working community.

5.9 Limitations of Study

The sample of participants used within this study represented a working population but the sample was biased towards younger participants, with the 18-29 year old age group containing over half of the sample. Conclusions drawn regarding age differences must be treated with caution. The lack of significant differences between age groups suggested, however, that an equal distribution would not have significantly altered the average strengths but may have enhanced the trends found during analyses regarding age differences.

Limitations of the experimental procedures included maintaining consistent motivational levels between and within subjects. In addition, regulating postural control of participants was difficult. Though efforts were made to provide enough flexibility in posture to imitate a true working environment, excessive differences in posture may have altered the strength values obtained for individuals.

Peak forces varied $\pm 5\%$ relative to the individual's actual strength. Variations were partially due to noise in the data, filtering procedures, and statistical artifacts. However, average strengths were on the order of 40N – 90N so these inaccuracies account for an error of approximately 2.0N – 4.5N. These errors must be considered during any application of this research, but significance depends on the context of employment.

5.10 Future Areas of Research

Future research in this area is needed to accurately predict single digit strength. Present work has not shown that multi-digit strength can be predicted with sufficient accuracy to replace the use of commercially available gauges. However, since no such gauge exists for the measurement of single digit strength, prediction models are the only technique available at this time for determining peak forces without performing direct measurements during the task of interest.

The regression models derived from this research were limited in their predictive abilities. An examination of the R^2 -adj values and standard errors suggested that more accurate models are needed for practical implementation. To accomplish this task, different predictor variables need to be investigated. As noted earlier, some of the anthropometric measures included in this study were found to be redundant and unnecessary for the generation of regression models. Elimination of these variables, and addition of other pertinent anthropometric measures (e.g. finger length), may improve the accuracy of new regression models. In addition, collection of more data within the older age groups would clarify the existence of any age differences and create a larger and more representative database that may alter some of the findings within this research.

6. CONCLUSIONS

This study was motivated by the need to understand the force capabilities of the fingers in a variety of tasks (couplings) and by the lack of such data in the literature. The frequent occurrence of upper limb injuries and musculoskeletal disorders has recently motivated research concerning the identification of risk factors and modifications to tools and workstations. Minimizing the percentage of hand and finger strength that is required to perform a task has been investigated as a means to reducing the risk of cumulative trauma disorders and other musculoskeletal disorders. Normative data regarding hand and finger capabilities is needed for the design of tools and tasks that fit within proposed safety guidelines. This study provided a database of human capabilities for common finger exertions.

Human capabilities of the fingers are important during the design process, but the knowledge of an individual's capabilities is necessary when evaluating specific situations or rehabilitative progress. When direct measurement of peak finger forces is difficult or impossible, predictive models provide estimates of force capabilities. This research derived models to predict finger strength during basic hand exertions when several easily obtainable measures are available. After examining a wide variety of such mathematical models, the results suggest that finger strength can be accurately predicted from easily obtained measures, although with only moderate accuracy.

FORCE-EMG RELATIONSHIP DURING COMMON HAND COUPLINGS

1. INTRODUCTION

The application of appropriate work design principles, during the design of tools and workstations that involve the use of the hand and fingers, may minimize upper extremity injuries within the workplace. Determination and integration of force requirements is an essential component of this process. This study supplements available knowledge concerning the prediction of forces generated by the hand and fingers by developing mathematical models that estimate these forces from electromyographic data of the forearm muscles.

Cumulative trauma disorders (CTDs) and other work-related musculoskeletal disorders of the upper limbs have become a major concern for industry. CTDs are believed to be caused by the chronic effects of repetitive stress on the tendons, tendon sheaths, muscles and nerves of the upper extremities (Armstrong, 1986a). Movements of the upper extremities, such as reaching, gripping and pinching, combined with repetition in a forceful and/or awkward manner are known contributing factors to the precipitation and aggravation of CTDs (Armstrong et al., 1982; Palanisami et al., 1994). Sustained muscle activity as low as 5% of an individual's maximum voluntary contraction may be cause for concern as local fatigue has been shown to develop at even those low effort levels (Sommerich, Marras, and Parnianpour, 1998). CTDs of the upper extremities are a primary cause of lost time and Workers' Compensation in hand-intensive industries (Armstrong, 1986b). The Bureau of Labor Statistics (1999) reports that 7% of all cases involving injuries that resulted in lost time during 1992-1997 were due to repetitive motion of the upper limbs. This percentage remained relatively constant (6-7 %) over the five-year period, indicating a need for continued research and efforts in reducing CTDs.

Upper extremity injuries can be minimized through intervention and the application of appropriate work design principles. The integration of human strength capabilities and minimization of force requirements during the design phase of hand

intensive tasks may reduce the risk of occupational injuries, including CTDs, and the costs associated with them (Armstrong, 1986a; Palanisami et al., 1994).

Procedures used to measure finger forces in vivo are extremely invasive and costly; therefore, alternative methods of determining levels of force must be developed. Instrumenting tools and workstations with force transducers is often impractical and sometimes impossible, and accurate measurements are generally difficult to obtain without interfering with the task to be performed. For example, instrumentation of products on an assembly line would be impractical if manipulation of the product is required (e.g. placing products in a box). A practical question thus arises as to whether force requirements during hand couplings can be estimated using non-invasive measures (e.g. electromyography) and thus allow the practitioner to monitor forces without a significant interruption of normal tasks. The objective of this experiment was to examine the relationship between finger forces and the level of muscle activity in the forearm using standardized procedures. Predictive models were developed using multiple linear regression. The goal in developing these models was to assess the feasibility of predicting finger forces from surface electromyographic (SEMG) measures. Such models help overcome the limitations of direct force measurements and allow for the estimation and minimization of force requirements during hand intensive tasks.

Electromyographic (EMG) signals provide information regarding the muscles that are used during a given action. These signals indicate (1) whether a given muscle or muscle group is active, (2) the relative activity of the muscle or muscle group, (3) information regarding the relative amount of force generated, and (4) the state of muscle fatigue through the analysis of the spectral components (Marras, 1990).

Past research has focused on the relationship (e.g. monotonicity or linearity) between muscle activity and the forces exerted during various activities. Predictive methods must be developed for each muscle group (e.g. trunk extensors, elbow, shoulder) because results cannot be generalized between muscles and may be further limited if the experimental conditions are notably different. There is a lack of data providing practical methods for estimating relative muscle requirements of the hand and fingers. Such methods, if proven to be reliable, have direct application in the design and evaluation of human-machine interfaces involving the whole hand or single digits.

2. REVIEW OF LITERATURE

Directly measuring the force produced by a muscle is invasive and costly, however, the force exerted during a task can be accurately measured using force transducers integrated into the working environment. Executing tasks while subjected to such conditions can interfere with normal work processes; thus, methods of indirect force estimation may be an efficient and reliable alternative. Analysis of EMG data is one such indirect measure, because the level of forces exerted depends on the activation and excitation of muscle fibers (Dowling, 1997; Perry and Bekey, 1981). EMG analysis is a potentially useful approach because it may be related to forces either in a specific manner, or generalized externally (e.g. by a limb or joint).

Prior to establishing a mathematical equation relating force and EMG, it is necessary to determine the form of the relationship. Several investigations have attempted to determine and describe the relationship between force and EMG signal amplitude in a general setting, but no consensus has been established (Dowling, 1997). Some studies have concluded that SEMG, after pre-processing using rectification and integration, varies linearly with force generated at a constant muscle length or during contractions with constant velocity (Milner-Brown and Stein, 1975). Woods and Bigland-Ritchie (1983) investigated the degree of linearity within the force-EMG relationship and found that linearity existed for muscles such as the adductor pollicis and soleus. Other muscles, such as the biceps and triceps, behaved non-linearly from 0-30% MVC, and then linearly above this range. In their study of elbow flexion, Moritani and DeVries (1978) determined that a linear relationship existed between the electrical muscle activity of the biceps brachii and the forces produced during exertions. In addition, a linear model was developed by Laursen, Jensen, Nemeth, and Sjogaard (1998) to predict shoulder forces during isometric contractions. Furthermore, Milner-Brown and Stein (1975) concluded that there was a simple linear relationship between SEMG and force within the first dorsal interosseus muscle of the hand. These findings show that the degree of linearity depends on the muscle being investigated, but many muscles seem to exhibit a linear relationship between force and EMG.

The degree of linearity may depend on the muscle being investigated, but other influential factors must be considered, such as sampling bias, synchronization, and tension non-linearities (Milner-Brown and Stein, 1975). Rate coding has been shown to increase the linearity of the force-SEMG relationship (Ray and Guha, 1983), whereas tension, length, and velocity characteristics within muscles are nonlinearities that affect the overall relationship (Perry and Bekey, 1981). Furthermore, Zuniga and Simons (1969) determined that there is a nonlinear relationship between averaged EMG potential and muscle tension. In addition to muscle characteristics, the electrode arrangement, type of measurement (continuous versus interrupted serial), fatigue, and level of physical conditioning level may influence the apparent force-EMG relationship (Zuniga and Simons, 1969). These diverse results reinforce the need for predictive models relating each muscle of interest with the force exerted.

Based on the information known regarding the force-EMG relationships of various muscles, different types of models have been developed to explain the form of the relationship and predict forces. It is recognized that the peak-to-peak amplitude of EMGs increases approximately as the square root of the recruitment force threshold for a muscle (Milner-Brown and Stein, 1975; Ray and Guha, 1983). Woods and Bigland-Ritchie (1983) stated that under isometric conditions, the relationship between integrated, smoothed, or rectified EMG and muscle force depends on the physiological characteristics of the muscle. If the muscle mechanics are known, they can be incorporated into a Hill-type model that can be used to predict muscle forces (Dowling, 1997). The development of generic prediction models has been less successful, perhaps due to variations in muscle composition.

Variations in procedures used to record and analyze EMGs also need to be considered when determining the relationship between forces and EMGs. Solomonow, Baratta, Shoji, and D'Ambrosia (1990) stated that it is necessary to incorporate the control strategy of the muscles being investigated, the force generation rate, joint angle, muscle length, and muscular coactivation. External interference, from long electrode leads or lead movement, may create noise and artifacts that will distort the signal (Marras, 1990). Distortion of the raw EMG signal may also occur if there is crosstalk from nearby muscles. Woods and Bigland-Ritchie (1983), however, determined that

changes in recording procedures, including variations in electrode placement, recording configuration and limb position, did not significantly alter the force-EMG relationship of the biceps and triceps brachii.

Characteristics of the muscle of interest may also influence the force-EMG relationship. Muscles of uniform fiber composition exhibit a linear relationship while a roughly even fiber mix is more nonlinear (Woods and Bigland-Ritchie, 1983). The predominant fiber type can also influence the linearity with slow twitch muscles behaving more linearly as compared to the non-linear characteristics of fast twitch fibers (Zuniga and Simons, 1969). Woods and Bigland-Ritchie (1983) stated that muscles display nonlinear behavior at lower forces due to selective recruitment of motor units at different distances from the electrodes. In addition, muscles that depend on frequency coding for force modulation demonstrate linear tendencies while muscles such as the bicep brachii recruit throughout the total range of force and behave nonlinearly, with the discontinuity at approximately 30% of the maximum voluntary contraction. Ray and Guha (1983) proposed that nonlinearities may be explained by supratetanic excitation and twitch tensions.

Limiting research to isometric contractions, to simplify the variables to be analyzed by minimizing movement, eliminates many of the tasks that are prevalent in industrial settings. Dynamic contractions, although more complicated to analyze and quantify (create mathematical models) due to the movement of body parts, must be studied in order to assist in understanding all risk factors present within working environments. Linear algebraic equations may not suffice when attempting to explain dynamic situations (Perry and Bekey, 1981). Perry and Bekey (1981) suggest relating the velocity of contractions and the tension produced with Hill's hyperbolic equation. When examining a dynamic elbow flexion, Wyss and Pollak (1984) considered action potential peaks of integrated EMG as a basis for a muscle model. The torque-EMG relationship of abdominal muscles required quadratic regression but still did not account for all of the variation around a linear regression line (Stokes, Moffroid, Rush, and Haugh, 1989).

Retesting participants for maximum isometric strength and EMG-torque relationship significantly affects these measurements in the rectus abdominis muscle (Stokes et al., 1989). Perhaps different recruitment strategies are learned during retesting

when using complex muscles. Therefore, careful attention is required when training is included in an experimental design.

The interaction of muscles during contractions must be accounted for during analyses. Principal components have been used to minimize the affects of multicollinearity, the overlapping affects of independent variables, but generalization may not be possible due to the large number of assumptions and specificity of the situations examined (Hughes and Chaffin, 1997).

In general, predicting forces is difficult because so many factors can influence the resulting exertion. The muscle being investigated, procedures implemented, and the form of the force-EMG relationship are vital components for accurately determining force levels. Various approaches have utilized relatively simple models under controlled conditions to determine forces produced by different muscles. Sommerich et al. (1998) studied typing tasks in an attempt to determine a dose-response relationship for general hand intensive tasks and create generic biomechanical assessments. Armstrong et al. (1982) used rectified EMG signals of the forearm flexor muscles to predict the finger forces produced during tasks involving pinching, grasping and pressing. Grant, Habes, and Putz-Anderson (1994) predicted grip force from EMG measures and ratings of perceived exertions, and reported that as much as 74% of the variation could be explained. Buchanan, Moniz, Dewald, and Rymer (1993), using EMGs and anatomical parameters, estimated isometric muscle forces about the wrist using an EMG coefficient method. Although there are limitations with this model, including the lack of repeatability and restriction to static isometric conditions, forces at the wrist could be estimated with coefficients of variation less than 10%. Several studies have examined muscle forces produced about the elbow. A multi-channel SEMG approach by Clancy and Hogan (1991) was used to develop a third order polynomial algebraic relation with an estimation error of approximately 3% to predict forces about the elbow. Furthermore, a model created by Wyss and Pollak (1984) approximated muscle forces about the elbow with 10% error. Extensive work has been conducted on the lumbar musculature during static and dynamic situations with EMG based models being predominant, although neural network models have also been used (Granata and Marras, 1993; Granata and

Marras, 1995; Hughes, Chaffin, Lavender, and Andersson, 1994; McGill, 1992; Nussbaum, Chaffin, and Martin, 1995).

A variety of single and multi-digit exertions commonly used in industrial tasks, having some form of hand- or finger-machine interface, were included in the set of experimental tasks within this study. Subjects performed six different couplings: three single digit force exertions and three multi-digit force exertions (see Methods). Kroemer (1986) and Jacobson and Sperling (1976) propose additional descriptions of couplings between the hand and controls that involve single and multiple digits, including couplings that loosely describe the single digit couplings included in this study. The set of hand-handle positions describes the primary positions that the hand maintains during force exertions.

Data pertaining to the prediction of finger force requirements during hand intensive tasks is absent in the literature. The present study avoided several of the earlier mentioned difficulties by examining isometric efforts, whereas many of the above studies examined dynamic tasks. These simplifications were intended to allow for an assessment of the feasibility of predicting finger forces from EMG measures. This study examined the feasibility of estimating finger forces from indirect measurements of force exertions without significant interruption within the working environment.

3. METHODS AND MATERIALS

3.1 Overview

This project investigated force-EMG relationships of the extrinsic finger flexors and extensors while forces were generated in different hand couplings. The feasibility of predicting hand and finger force levels from surface EMG was determined while using standardized procedures. As part of these experimental goals, the following hypotheses were formulated:

Hypothesis 1: The force-EMG relationships of the extrinsic finger flexors and extensors can be reasonably estimated using simple linear models.

Hypothesis 2: Finger force levels during hand intensive tasks are predictable from surface EMG while using standard electrode placements.

3.2 Experimental Design

The experiment was a full factorial, repeated measures design. Subjects performed maximum voluntary exertions in six different couplings, with three trials per coupling, for a total of 18 trials. Two types of dependent variables were measured, consisting of force and EMG levels. Conditions were performed in a fully randomized order to avoid confounding order effects.

3.2.1 Experimental Conditions.

Six particular hand couplings were chosen to simulate a variety of hand intensive tasks that are commonly performed in industrial settings. For example, pushing buttons, sliding levers, and inserting fasteners all require single or multi-digit couplings similar to those investigated in this study. The couplings investigated are described and illustrated in Figure 2 through Figure 7.

3.3 Participants

Thirty volunteers, between 18 and 24 years of age, were selected from the community. There were an equal number of female and male participants. Participants within a small age range were used to minimize potential confounding effects of age. All

participants were in good health and did not have a history of upper limb pain or musculoskeletal injuries within the last six months.

Participants were identified in the study using a coding scheme to maintain anonymity (e.g. Subject 1 = S001). All subject information and data sheets were kept confidential through the course of the study and upon completion of the data analysis. The participants were compensated for their time and participation, and were allowed to withdraw from the study at any time without penalty.

3.4 Apparatus and Materials

The experimental environment simulated seated work. An adjustable chair was used to alter the seat height and armrest heights as necessary to accommodate different sized participants. The use of the same chair and table (height 66cm) allowed for standardization of posture between subjects.

3.4.1 Maximum Voluntary Force Measures.

A strain gauge force transducer was used to determine forces exerted by the finger(s) during experimental trials. The pinch gauge used resembled commercial pinch gauges, but allowed for continuous recording of pinch forces. The gauge consisted of two identical aluminum bars held together at their bases. Forces applied at a designated area caused a voltage change as a result of the deformation of the strain gauges that were mounted on the pinch gauge. The pinch gauge was wired to accommodate either a half or full Wheatstone Bridge arrangement depending on the task being performed.

Prior to the recording of any data, the strain gauge force transducer was calibrated and zeroed at no load. It had been previously determined that there was a nearly linear relationship between the voltages produced by the strain gauge force transducer and the forces applied to the instrument (see Apparatus and Materials pages 15 - 17).

LabVIEW™ data acquisition software was used to collect and convert voltages from the strain gauge force transducer. Raw voltages from the strain gauge system were A/D converted, sampled at 1024Hz, low pass filtered (Butterworth, 2nd order, 10Hz cutoff), and converted to units of force (N).

3.4.2 Electromyographic (EMG) Activity Level.

Electromyographic signals from three muscle groups of the forearm were recorded by using disposable surface electrodes (2 cm x 4 cm) and an amplification system. Measurements were taken from the extensors on the dorsal side of the forearm, primarily evaluating the muscle activity of the extensor carpi ulnaris and extensor digitorum. Two flexor muscle groups were investigated, both located on the ventral side of the forearm: (1) flexor carpi radialis, and (2) flexor carpi ulnaris and palmaris longus. Although surface electrodes primarily measured the activity levels of the muscles indicated, crosstalk may have occurred from the deeper muscles within the forearm. These included, but were not limited to: flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus, extensor digiti minimi, extensor pollicis longus, extensor pollicis brevis and abductor pollicis longus. Procedures for electrode placement are given below. Raw EMG signals were preamplified (x100) near the electrode site, hardware amplified (to ~5v) and filtered (30-1000Hz), integrated (55ms time constant), A-D converted and sampled at 100Hz.

3.5 Experimental Procedures

At the onset of the experiment, the participants received verbal and written information concerning the purpose, methods, and intent of the experimental procedures using a standardized set of instructions. The participant was given the opportunity to ask any questions pertaining to the study. The participant was then required to read and sign an informed consent that had been approved by the Virginia Polytechnic Institute and State University IRB Committee (#97-266) and received a copy of the consent form to retain for their records. As part of this process, participants were screened for chronic upper body musculoskeletal conditions and acute injuries that had occurred within the previous six months. Participants were informed within the written instructions to notify the experimenter if they were experiencing any pain or discomfort or had been injured within the past six months. In addition, the experimenter verbally asked the participant the same question before proceeding. Upon completion of the informed consent, the experimenter recorded the participant's gender, age, dominant hand and anthropometric data.

Participants were read a set of general instructions prior to any force exertions. The experimenter read the instructions in order to maintain consistency and standardization between participants. The general instructions included a description of the procedures that were followed when the participant performed the force exertions.

The force exertions were performed using the participant's dominant hand while seated. Participants were instructed to maintain a standard position for grip and pinch strength measurements. This position (Fess and Moran, 1981) required an upright posture with feet on the floor while the shoulder was adducted, elbow flexed at a 90-degree angle, and the forearm and wrist in a neutral position. The chair supported the nondominant arm in an effort to allow the participant to concentrate on the task and focus all of their efforts on maximizing the force produced.

Past studies of hand and finger strength have concentrated on a sustained maximum exertion and commonly used the Caldwell Regimen (Caldwell et al., 1974). In contrast, subjects in the current experiment were not required to *sustain* a maximum force exertion but only to provide a peak exertion. This procedure was previously explained in detail, including examples of acceptable and unacceptable trials (see Experimental Procedures pages 18 – 20).

Immediately following the general instructions, the subject was prepared for the EMG measurements. The area of the subject's dominant forearm where the electrodes were placed was shaved free of hair, cleaned, abraded and cleaned again with alcohol. Interelectrode resistance was maintained at less than 10 k Ω . The electrodes required 20 minutes to stabilize so the measurement of the resistance was repeated at that time if the original reading was not acceptable. If needed, additional cleaning and abrading of the forearm was used to reduce the resistance between electrodes. Electrodes not meeting this requirement were replaced. An additional electrode was placed on the ulnar styloid process (wrist bone) to ground the system. After the electrodes were in place and the resistance between them was acceptable, the lead wires were taped to the forearm of the participant with no tension in the wires to prevent artifacts due to lead movement. Placement of the lead wires and preamplifier allowed for movement of the arm without pulling on the lead wires.

Surface electrodes were placed in pairs over each muscle group investigated. The electrodes were oriented parallel to the muscle fibers with the centers being placed 2cm apart. Placements of the electrodes were determined from standard techniques provided in Zipp P. (1982). The electrodes for the first group of flexors were placed $\frac{2}{3}$ of the distance from the styloid process of radius to the medial epicondyle of humerus with the second electrode placed proximally (Figure 24). The electrodes for the second group of flexors were placed $\frac{3}{4}$ of the distance from the sulcus carpi to the medial epicondyle of humerus with the second electrode placed proximally (Figure 25). The electrodes for the extensor group were placed $\frac{2}{3}$ of the distance from the styloid process of the radius to the medial epicondyle of humerus with the second electrode placed proximally (Figure 26).

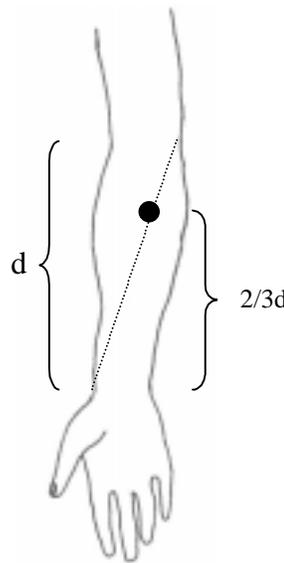


Figure 24. Electrode placement for recording Flexor I signals.

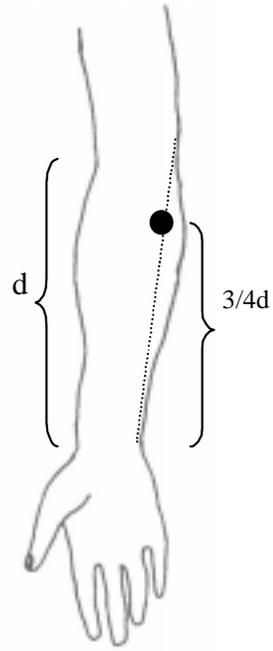


Figure 25. Electrode placement for recording Flexor II signals.

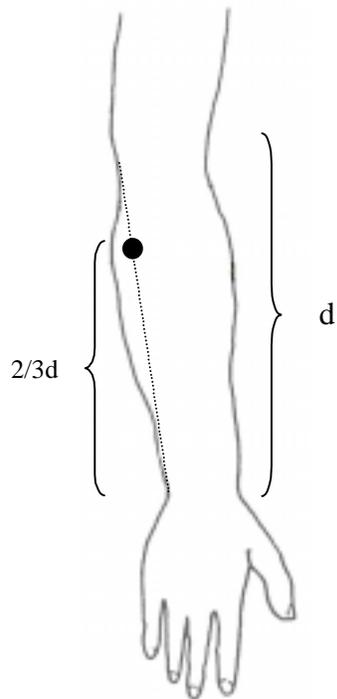


Figure 26. Electrode placement for recording Extensor signals.

Following the placement of electrodes, while performing simple wrist flexion and extension movements, an oscilloscope was used to confirm the quality of the EMG signal. Prior to collecting any data, the gain was established for each channel (muscle group) being investigated while the participant performed maximum voluntary exertions (MVEs). Amplifier gains were set (during MVEs) to yield voltages of approximately $\pm 5V$. Maximum and minimum EMG values were recorded for each muscle group for subsequent EMG normalization.

After the preparation of the equipment, a practice session was begun with the reading of a detailed description of each force exertion and demonstration of the coupling by the experimenter. The participant was given an opportunity to practice each coupling at a submaximal exertion level in order to feel comfortable with the coupling and the ramping procedure. The execution of one or two submaximal trials was usually sufficient. The practice session was intended to facilitate the participant's ability to perform the six couplings and ramping procedure with consistent success. Efforts were made to provide enough practice for the individuals to successfully learn the procedures during the submaximal practice trials.

Prior to each trial, the experimenter identified the coupling and prepared the equipment for that specific trial. When signaled by an auditory signal (computer-generated "beep") the participant performed the trial as previously instructed. Each trial took a total of approximately three to five seconds. Immediate feedback on the computer display allowed the experimenter to identify if the data was acceptable, or if the trial had to be repeated. After an acceptable trial, the experimenter identified the next condition and reset the equipment while the participant rested for a minimum of two minutes to allow for recovery. Participants were encouraged to request more rest, or notify the experimenter, if any symptoms of fatigue were felt at any point during the experiment.

3.6 Data Analysis Protocol

The forces produced during the exertions were collected along with the root mean square EMG for each muscle group. Prior to any analysis, all force and EMG data was software filtered (2nd order Butterworth), using a cutoff frequency of 2.0 Hz, and normalized using the equation below.

$$\text{NormalizedEMG}(NEMG) = \frac{EMG_i - \text{RestingEMG}}{\text{MaximumEMG} - \text{RestingEMG}}$$

For each finger coupling, multiple linear regression models were developed using normalized EMG (NEMG) measures as predictor variables. The models were evaluated using linear regression (measured vs. predicted forces) and the associated adjusted coefficients of determination (R^2 -adj) and standard errors. In addition, the significance of the parameters included in the models was considered.

Analyses were performed on each exertion as a whole, and also separately for the ascending and descending portions of the force curve. The division was determined by identifying the maximum force and then splitting the force and NEMG at this point. For each trial, therefore, three separate regression models were created and evaluated (whole, ascending, descending).

Analyses of variance (ANOVAs) were performed to determine significant differences in the measures of model performance when calculated for the whole exertion as compared to those for the ascending and descending portions. Furthermore, ANOVAs were used to identify any significance of the subject, coupling, or interaction effects.

4. RESULTS

4.1 Graphical Data

An example of a lateral pinch following the procedures outlined in the Methods is provided in Figure 27. Plots of the other couplings differed in magnitude but maintained a similar shape.

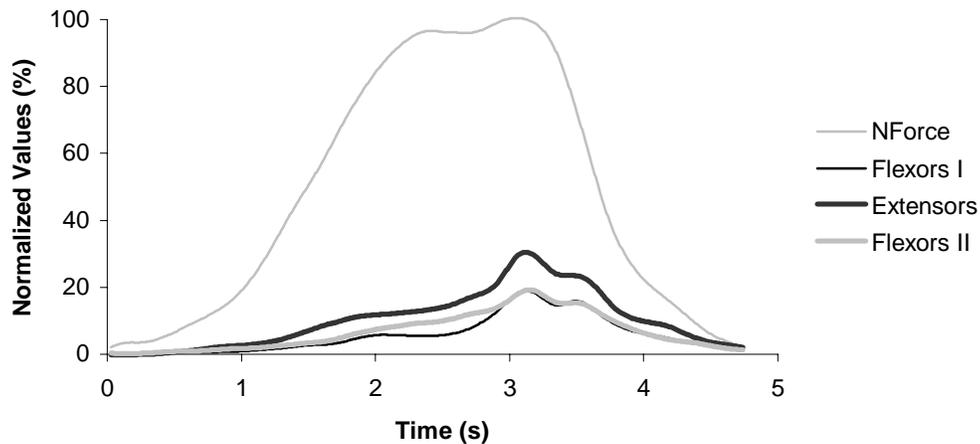


Figure 27. Normalized force (Nforce) and normalized electromyographic curves (Flexors I – NEMG1; Extensors – NEMG2; Flexors II – NEMG3) for a typical force exertion (lateral pinch).

An illustration of the muscle activity associated with varying force exertion levels is provided in Figure 28. The curves show the changes in the NEMG associated with the increase and decrease of force. The substantial differences in NEMG measures as force was increased and decreased, illustrating the motivation of a division of the data and separate analyses, divided the data into two portions (ascending and descending). Additionally, initial and concluding NEMG signals that corresponded to force levels below 2% of the maximum force were eliminated from analysis.

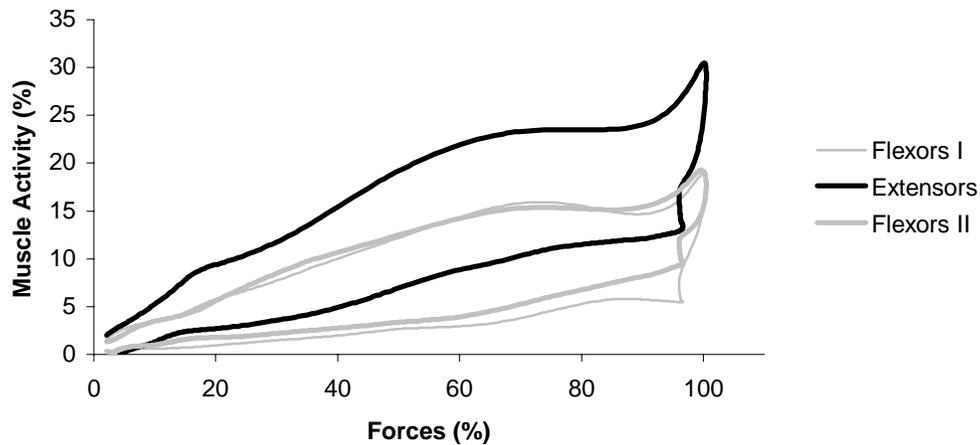


Figure 28. Muscle activity present at varying levels of force during the increase and decrease of force.

4.2 Models for Prediction of Finger Forces

Multiple linear regression was used to generate models to predict the value of the dependent variables (finger forces) using the independent variables (NEMG). Accuracy of the models was determined from the adjusted coefficient of determination (R^2 -adj) that provided an overall measure of performance adjusted for the number of model parameters. The standard error of the regression model was also used to quantify prediction error. Both measures facilitated comparisons between models.

Multiple linear regression models were created and analyzed based on the data collected for all subjects and for each of their exertions. This included three trials for each coupling per subject. Models were created for the entire exertion (whole), as well as the ascending and descending portions.

The multiple linear regression models included all three NEMG measures as predictor variables. An example of models derived for the above lateral pinch, including R^2 -adj and standard error values, is shown below for the whole trial (a), and ascending (b) and descending (c) portions.

(a) $Lateral\ Force = 1.73 - 15.97NEMG1 + 10.38NEMG2 + 4.61NEMG3$
 $R^2\text{-adj} = 0.95$; standard error = 8.60N

(b) $Lateral\ Force = 5.32 - 11.99NEMG1 + 9.15NEMG2 + 3.45NEMG3$
 $R^2\text{-adj} = 0.97$; standard error = 6.73N

(c) $Lateral\ Force = -10.31 - 2.27NEMG1 + 4.96NEMG2 + 0.22NEMG3$
 $R^2\text{-adj} = 0.97$; standard error = 5.54N

NEMG1: Normalized EMG for Flexors I

NEMG2: Normalized EMG for Extensors

NEMG3: Normalized EMG for Flexors II

The measures of model performance for the above example were within the ranges of values found for the data collected, but the $R^2\text{-adj}$ values were slightly higher than average and the standard error values were lower than average.

For this trial, plots of measured forces versus predicted forces are provided in Figure 29, Figure 30, and Figure 31. The linear regression line represents a plot for a model with 100% predictive accuracy. The plots indicate a close fit between the measured and predicted forces while exhibiting a linear trend. Variations from linearity existed that could not be accounted for, particularly in the portion of the trial when the measured forces were held near the maximum value (Figure 29 and Figure 30).

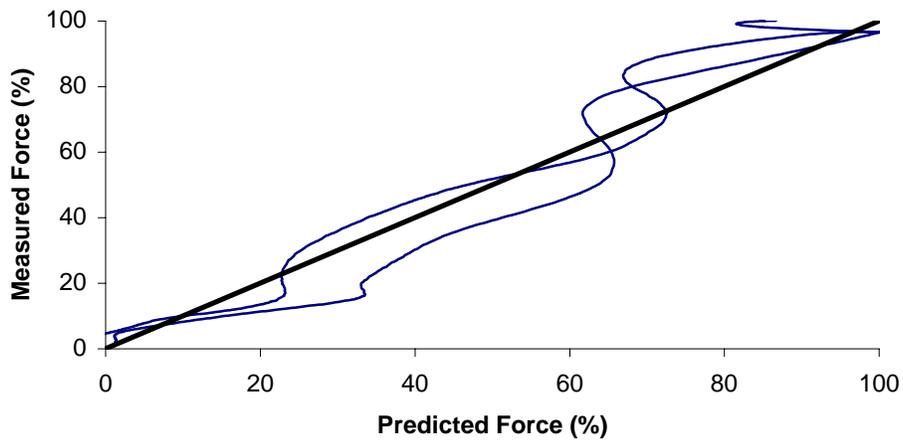


Figure 29. Measured versus predicted forces (percent of maximum) for the whole task (R^2 -adj = 0.95, standard error = 8.35N). A linear regression line has been superimposed on the curve for comparison.

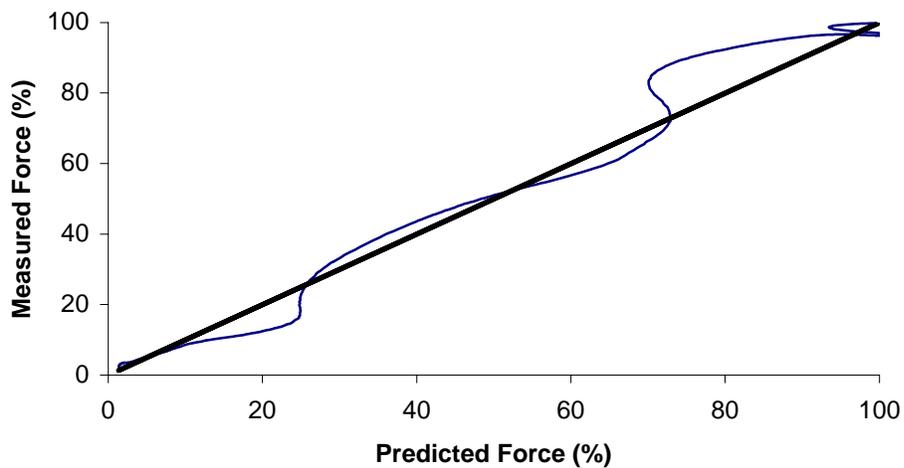


Figure 30. Measured versus predicted forces (percent of maximum) for the portion of the task associated with an increase in force (R^2 -adj = 0.97, standard error = 6.73N). A linear regression line has been superimposed on the curve for comparison.

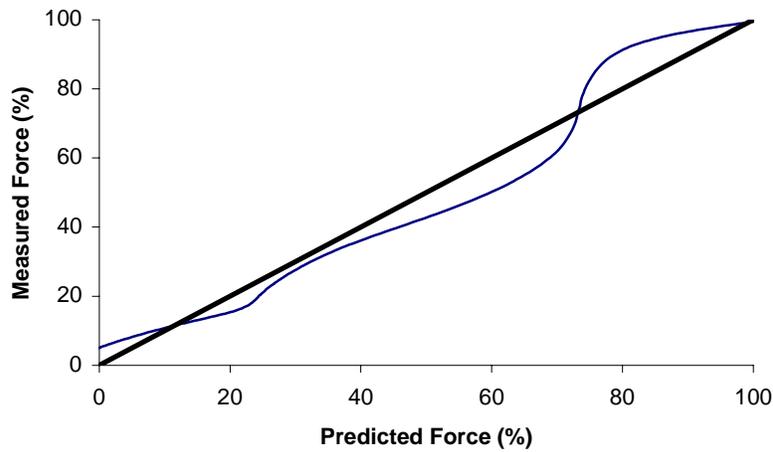


Figure 31. Measured versus predicted forces (percent of maximum) for the portion of the task associated with a decrease in force (R^2 -adj = 0.97, standard error = 5.54N). A linear regression line has been superimposed on the curve for comparison.

In contrast to the above example, some trials yielded models that resulted in relatively poor estimation of force levels. An example of a “bad trial” for a 90-degree distal pad pull is provided for comparison (Figure 32 and Figure 33). Although the normalized forces were within the acceptable guidelines, the NEMG for this trial did not vary due to force. The magnitudes of the NEMG curves differed, but fluctuations appeared random. No relationship between the normalized forces and NEMG seemed to exist.

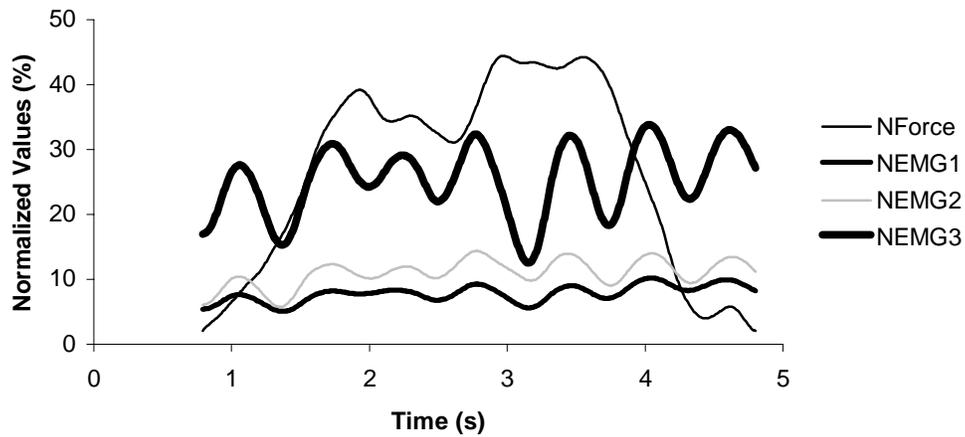


Figure 32. Normalized force and normalized EMG curves for a “bad” force exertion (90-degree distal pad pull).

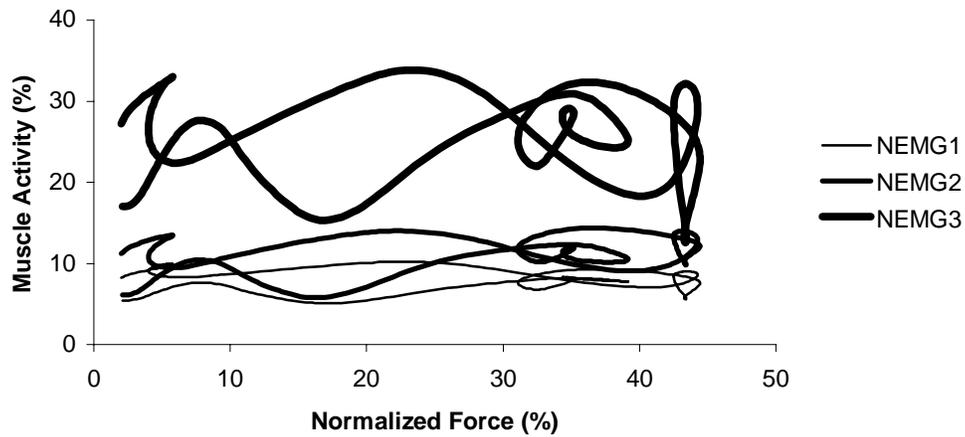


Figure 33. Muscle activity present at varying levels of force during the increase and decrease of force.

For this trial, plots of measured forces versus predicted forces are provided in Figure 34 and Figure 35. The plots indicated a linear trend but less of a close fit between the measured and predicted forces relative to the “good” trial. Larger variations from linearity existed that could not be accounted for, particularly at lower force levels.

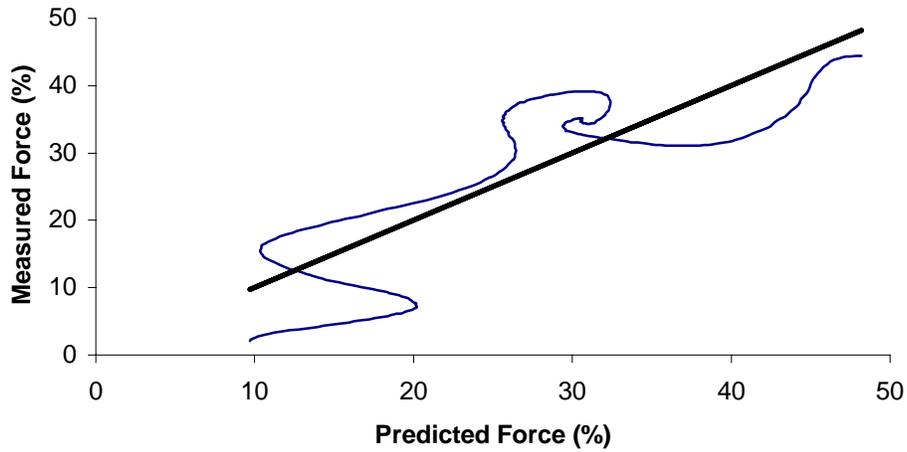


Figure 34. Measured versus predicted force for the portion of the task associated with an increase in force (R^2 -adj = 0.70, standard error = 6.82N).

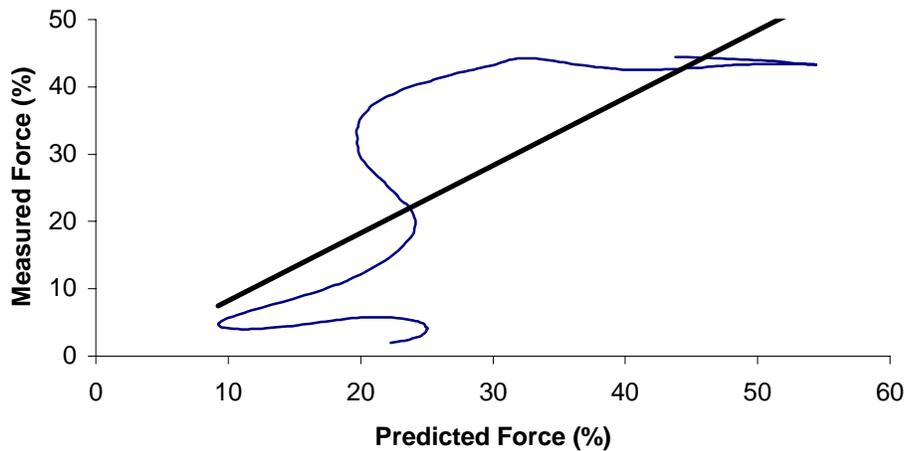


Figure 35. Measured versus predicted force for the portion of the task associated with a decrease in force (R^2 -adj = 0.64, standard error = 10.14N).

4.3 Model Performance

Regression output was classified into the three categories described above (whole, ascend, descend) and several measures were compiled. These measures included the adjusted coefficient of determination (R^2 -adj), standard error, regression parameters (b_1 , b_2 , b_3) and the associated p-values for these NEMG parameters. In addition, the

significance of parameters was determined based on an alpha significance level of 0.05. Lastly, the number of significant parameters was recorded for each model created (range: 0 to 3).

A significant ($p < 0.05$) difference in R^2 -adj values was found between the six couplings (Figure 36). R^2 -adj values were on the order of 0.85 with the values being consistently lower for the analyses of the whole exertion. An ANOVA ($p < 0.001$) verified that this difference was statistically significant. R^2 -adj values were somewhat higher for multi-digit couplings (lateral pinch, three-jaw chuck pinch, palmar pinch), but these differences were not substantial.

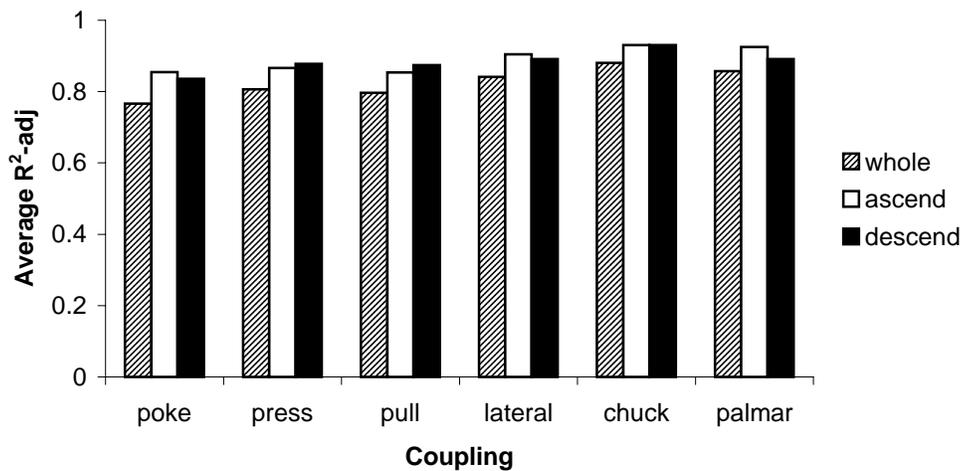


Figure 36. Average R^2 -adj values for the different couplings comparing across the three exertion classifications.

A significant ($p < 0.05$) difference in standard error values was found between the six couplings (Figure 37). Standard error values were on the order of 10N with the values being consistently higher for the analyses of the whole exertion. An ANOVA ($p < 0.001$) verified that this difference was statistically significant. Standard error values were somewhat lower for three-jaw chuck and palmar pinch, but these differences were not substantial. No consistent trends existed for the standard error values.

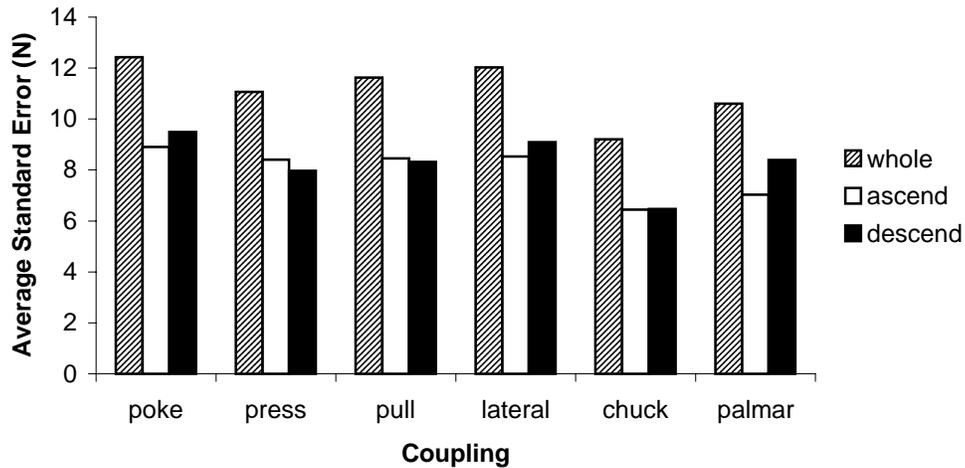


Figure 37. Average standard error values for the different couplings comparing across the three exertion classifications.

4.4 Model Parameters

The number of significant parameters in the regression models differed depending on the coupling and was determined and averaged for all models (Figure 38). The average number of parameters that were significant within the regression models was approximately 2.7 for all couplings and all exertion classifications. A slight, but statistically insignificant, increase was shown for the analyses considering the whole exertion (2.7 – 2.8), relative to the ascending (2.6 – 2.8) and descending (2.5 – 2.7) portions. Additionally, no difference was noticeable between the single digit couplings (2.5 to 2.8) and the multi-digit couplings (2.6 – 2.8).

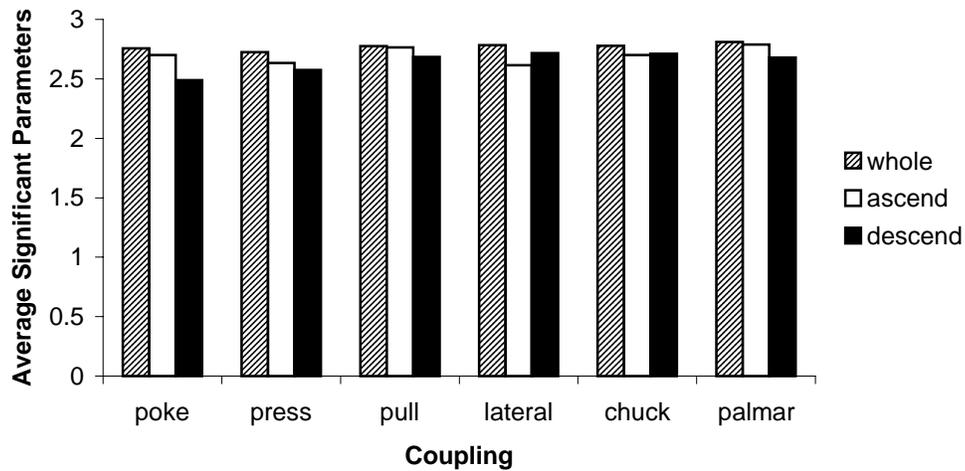


Figure 38. Average number of significant parameters included in the regression models for the three exertion classifications.

The frequency with which each particular parameter was found significant, indicating the necessity of the associated NEMG measure, was not significantly different between couplings and exertion classifications. Regardless of the coupling or exertion classification, the parameters were found to be significant approximately 90% of the time, ranging from 78% – 98%. On average, the parameters were significant in more models when the whole exertion (92%) was considered (Figure 39), relative to the ascending portion (Figure 40) and descending portion (Figure 41), 90% and 88%, respectively. Furthermore, the extensors were significant in 92% of the regression models, which was slightly higher than the first group (88%) and second group (90%) of flexors.

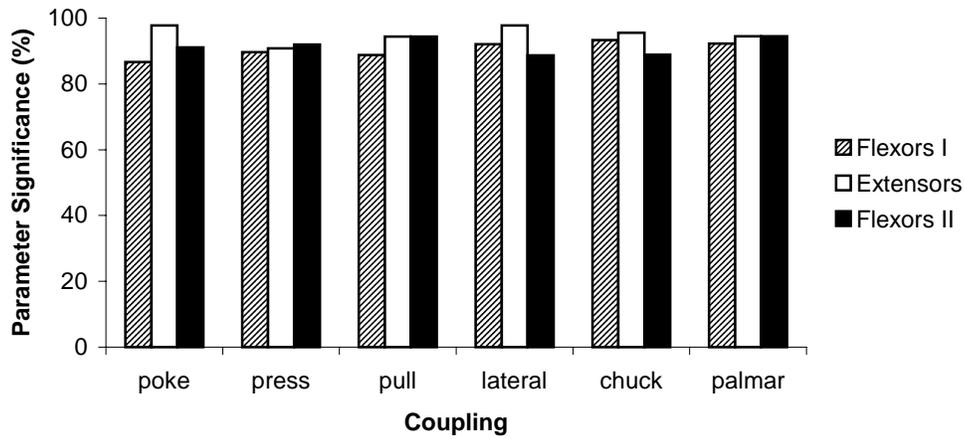


Figure 39. Percentage of regression models in which the parameters were found to be significant when considering the whole exertion.

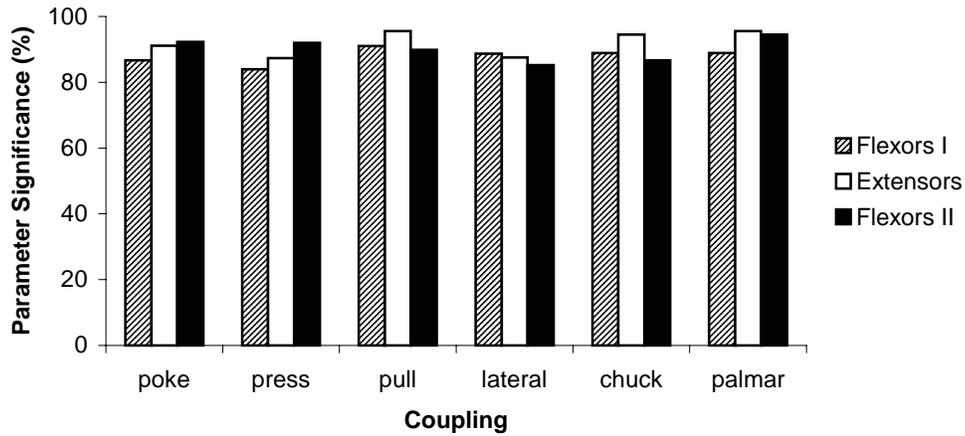


Figure 40. Percentage of regression models in which the parameters were found to be significant when considering the ascending portion of the exertion.

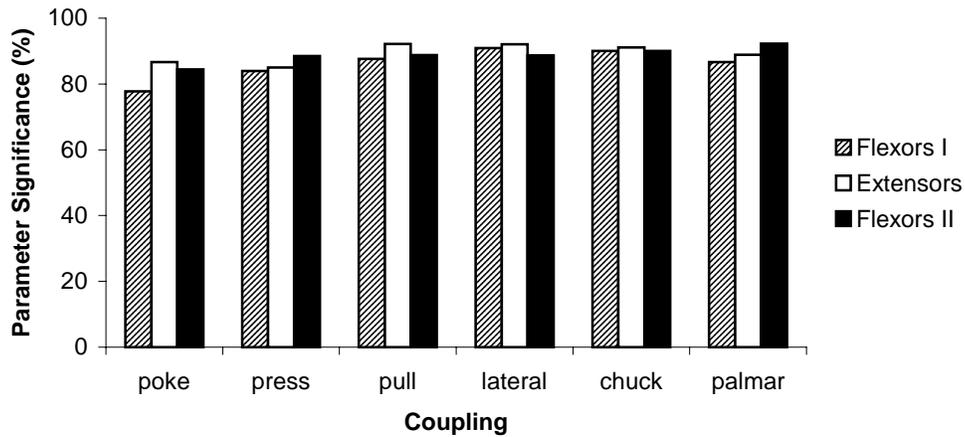


Figure 41. Percentage of regression models in which the parameters were found to be significant when considering the descending portion of the exertion.

The parameter values (b_1 , b_2 , and b_3) provided additional information about the contribution of particular NEMG measures in the regression models. The magnitude of the parameters indicated the influence of the corresponding NEMG measure in predicting the finger force. Table 11 summarizes the descriptive statistics for the regression parameters used to predict forces exerted in the different couplings. The parameter values for the extensors were not always the largest (0.7 – 5.9), but they were consistently positive on average. The first group of flexors were associated with the largest parameter values (-6.0 – 7.9) and the largest range in average values. The second group of flexors corresponded to negative parameter values (-5.9 – 4.9), although the first and second group of flexors were never both associated with negative parameters within the same model. Parameter values were widely dispersed, indicated by large standard deviations and extremely wide ranges between minimum and maximum values.

Table 11. Summary characteristics for the regression parameters determined when analyzing each coupling for the whole exertion (b_1 :first group of flexors; b_2 :extensors; b_3 :second group of flexors).

	Parameter	Mean	Standard Deviation	Minimum	Maximum
Poke	b_1	-5.0	21.9	-59.4	99.3
	b_2	5.8	8.8	-36.1	46.0
	b_3	1.1	9.9	-49.3	27.2
Press	b_1	-6.0	24.6	-77.9	103.6
	b_2	0.7	10.2	-35.4	24.5
	b_3	4.9	8.1	-17.9	39.8
Pull	b_1	7.9	12.1	-35.9	46.2
	b_2	5.1	5.5	-12.8	25.0
	b_3	-5.1	6.6	-25.1	11.0
Lateral	b_1	7.0	13.9	-16.6	85.2
	b_2	5.9	6.5	-6.5	44.9
	b_3	-5.9	8.7	-62.2	5.5
Chuck	b_1	2.0	9.8	-74.0	24.1
	b_2	2.7	3.4	-16.3	17.1
	b_3	-2.2	3.0	-9.0	9.1
Palmar	b_1	3.3	35.3	-308.7	48.4
	b_2	1.8	17.5	-159.7	13.7
	b_3	-1.6	27.7	-23.4	253.2

5. DISCUSSION

Hand intensive tasks are common in industry and lead to chronic and acute injuries of the upper limbs for many individuals. Minimizing frequent forceful motions may reduce the occurrence of upper limb musculoskeletal and cumulative trauma disorders. Therefore, it is important to identify high-risk tasks by recognizing hand intensive tasks that require high force levels. Determining the force requirements of common hand intensive tasks can be accomplished by direct measurement of forces although these procedures can be cumbersome and intrusive. Using predictive models to indirectly estimate force requirements, based on SEMG measures, is an alternative approach. Many hand intensive tasks replicate one or more of the couplings used in this study. In addition to the strength data, NEMG data was collected at three standard locations on the forearm. Regression models were generated for each individual, based on NEMG measures, to predict finger forces in each coupling.

5.1 General Comments

Specific guidelines regarding the exertion of force were provided for all of the couplings. Each trial contained a time period where the participant was increasing force and then a subsequent period of time where force was decreased. Examination of NEMG behavior during the changes in force illustrated an inherent hysteresis (Figure 28). At this time it is not known what caused the behavioral changes in the NEMG measures. It may simply have been caused by the differing activity within the muscles during the shortening and lengthening phases of the exertion. The phenomenon was not unique to this research, however. Past research, including Stokes, Rush, Moffroid, Johnson, and Haugh (1987) and Stokes et al. (1989), determined EMG – torque relationships by dividing the exertions into two portions. Similar to preliminary findings of this study, Stokes et al. (1989) found that the slopes were greater for the increasing parts of the recordings. Although the EMG-torque relationship was found by Stokes et al. (1989) to be different between the two portions, no analysis was performed on the whole exertion for comparison. In the present study, exertions were analyzed as a whole and in two portions, but an explanation of the hysteresis effect was beyond the scope of the research.

An ANOVA was performed on the data within this study and showed a statistically significant difference between results based on the whole exertion and those based on the ascending and descending portions. Examination of the data, however, did not show an obvious practical difference. The largest differences were found between the standard error values (on order of 2N) but any practical significance of this difference can only be determined based on the application. The additional calculations and complexity of the analysis procedures may not make the division of the data worthwhile.

5.2 Models for Prediction of Finger Forces

The multiple linear regression models generated contained all three NEMG measures as predictor variables. Average values of the measures of model performance (R^2 -adj and standard error) were calculated to determine the feasibility of using this procedure to predict finger forces based on NEMG measures. The significance of the regression parameters determined the necessity of including the associated NEMG measure in the regression model as a predictor variable.

Predictive accuracy was high for the multiple linear regression models in the three exertion categories. Dividing the exertion into two portions significantly improved predictability, as shown by higher R^2 -adj values (0.84 – 0.93) for the ascending and descending analyses. However, the R^2 -adj values for the whole exertion were still moderately high (0.77 – 0.88). In addition, standard errors were lower for the separate portions (6.45N – 9.50N) relative to the whole exertion (9.21N – 12.42N). Given peak forces (43N – 81N) for single and multi-digit couplings (see Table 2), the standard error values were approximately 10% – 20% of finger strength values, which was considerably less than the coefficients of variation calculated (on order of 40%). Therefore, considering the large variation in muscle strength, the standard errors were determined to be reasonable.

No obvious differences were apparent between the couplings for the R^2 -adj and standard error values. A slight average increase in R^2 -adj values and decrease in standard errors existed for the single digit couplings, but a larger sample would be required to substantiate this trend. An absence of differences would indicate that all couplings could be predicted from the three standardized NEMG measures with equal accuracy.

It was not expected that every predictor variable would be significant for all of the regression models. Calculations were made to determine the percentage of trials where the parameter was significant for a regression model. Each parameter was considered separately for each of the exertion classifications.

The first flexor group was found to be significant in 87 – 93% of the regression models based on the whole exertion. Comparably for the ascending and descending portions, it was significant in 78 – 91% of the regression models. The extensors and second flexor group were also found to be significant in a high percentage of regression models for the whole exertion categorization (89 – 98%) and the ascending and descending portions (85 – 96% and 84 – 92%, respectively). These high percentages suggest that all three NEMG measures are necessary for accurate prediction.

The use of only one NEMG measure would reduce the predictive accuracy of the regression models. There were no obvious consistencies across couplings for the regression parameters; instead, the contribution of an NEMG measure was dependent upon the coupling. The magnitude of the parameters was similar for the 90-degree distal pad pull and the lateral pinch, and for the three-jaw chuck pinch and the palmar pinch. Generalizability between these couplings might be possible, but specifying one NEMG to be used to predict finger forces was difficult without further analyses. The two groups of flexors seemed to negate each other, suggesting that both were not necessary. However, the elimination of both groups of flexors might be detrimental for particular couplings, particularly the press.

Results of the present study were based on the generation and evaluation of linear regression models. The measures of model performance indicated that reasonable estimates were generated across the hand couplings (high R^2 -adj values and reasonable standard error values). Furthermore, although a conclusion could not be determined regarding the linearity of the force-EMG relationship, simple linear models provided adequate estimates of finger forces based on surface EMG measures obtained while using standard electrode placements. Therefore, the present study failed to reject both proposed hypotheses.

5.3 Limitations

Suitable analysis of the force and NEMG data relationship begins with accurate measurements. Regulating postural control of participants was difficult, although efforts were made to provide enough flexibility in posture to imitate a true working environment. Excessive differences in posture may have altered the strength values obtained for individuals. The size of the electrodes and the forearm of the individual limited the placement of two pairs of electrodes on the forearm to measure muscle activity of the flexors. For smaller participants, proper placement of both electrode pairs was difficult without overlap, which would have resulted in improper measurements. Replication of the experiment using smaller electrodes would identify if the NEMG values were altered for such individuals.

Normalization of the EMG measures required maximum voluntary exertions of the participants for each muscle group. Actual maximums were difficult to obtain due to the difficulty in identifying exertions that would isolate the desired muscle and uncontrollable motivation levels of the participants.

Other factors that may have altered the accuracy of the NEMG measurements included noise in the data and extraneous muscle activity. The muscles that control the wrist and maintain elevation of the hand are also located in the forearm. Muscle activity from these locations may have been measured inadvertently, in addition to the desired muscle activity since surface electrodes were utilized and crosstalk could not be completely avoided.

The development of accurate prediction models required an analysis of the force measures and the corresponding NEMG measures at that point in time. However, there existed a force-NEMG lag time such that the corresponding forces measured occurred slightly later in time than the corresponding NEMG measures. At this point no adjustment was made to the data collected. An adjustment, however, would only have improved the accuracy of the prediction models.

The regression models generated were not generalizable to other individuals or couplings. Every individual required a regression model for each coupling. The significance of this limitation is based on the context and extent of the application. The regression models within this study were generated from the same data that they were

predicting. Internal consistency of the models did not indicate the ability of the models to predict submaximal time-varying finger forces using the same hand couplings.

5.4 Comparisons to Other Research

Although there has been research performed that has predicted forces and torques for other parts of the body and various exertions, no research to date has attempted to predict single digit forces from NEMG measures of the forearm. There has been some success using EMG to predict hand and multi-digit forces. Armstrong et al. (1982) estimated finger forces for six hand couplings (pulp grasp, medial grasp, pulp pinch, palm pinch, and finger press) based on forearm surface EMGs but no quantitative results were given. Grant, et al. (1994) predicted grip force from EMG measures and ratings of perceived exertions with accuracy as high as 74%. Findings within the present study for finger forces were higher, but the discrepancies in predictive accuracy may have been due to the use of submaximal dynamic grasping tasks by Grant et al. (1994), which required postural changes during exertions. Furthermore, Buchanan et al. (1993) generated regression models based on EMG measures with similar accuracy ($R^2 = 0.62 - 0.88$) to predict forces at the wrist.

5.5 Applications

Individuals performing hand intensive tasks with high force requirements risk injuries, such as musculoskeletal and cumulative trauma disorders. Direct measurement of forces can be intrusive and even impossible during hand intensive tasks. Alternatively, measuring NEMG levels within the forearm can be accomplished using noninvasive techniques. In addition, NEMG measures record real-time submaximal data for the entire task as opposed to a single peak force. This data can be combined with predetermined regression models to determine the force requirements for the tasks being performed. Determining force requirements is an essential requirement for identifying high-risk tasks.

External validity of the regression models would permit generalization to predicting finger forces during time-varying submaximal trials, contrary to the present study that determined the predictability of data within the same trial. To test the external

validity, a poke was performed with varying submaximal force levels. Measured and predicted forces were compared (Figure 42) to determine predictive accuracy.

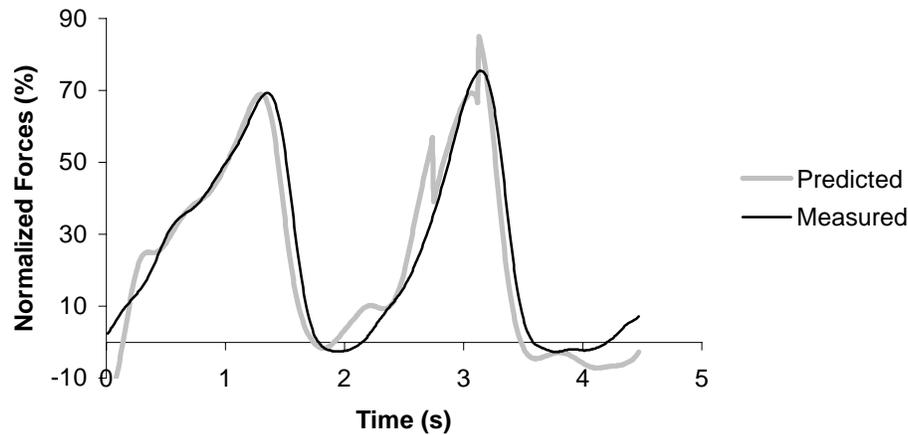


Figure 42. Measured and predicted forces for a submaximal time-varying exertion using the poke hand coupling (R^2 -adj = 0.91; standard error = 7.9%).

Further exploration must be performed to assess the feasibility of predicting finger forces for all of the hand couplings used in this study. Furthermore, more complex tasks must be considered to determine the generalizability to industrial tasks.

Regression models can also be used during the design phases of hand tools and hand intensive workstations. After the development of a prototype, EMG levels during use help to determine the percentage of force strength needed to perform the task. Comparing these percentages to safe guidelines can help designers create equipment that minimizes risk to the user.

5.6 Future Research Areas

Further work is needed to determine the feasibility of creating regression models, based on peak force data and the corresponding NEMG measures, to predict submaximal time-varying finger force levels. Current results were limited to measuring model performance based on data for the trial used to develop the model. The accuracy within the trial may not be a reliable indicator of general predictability.

The predictive models generated in this study were based on an assumption that the force-NEMG relationship would be linear. This assumption was partially based on previous research that determined a linear force-EMG relationship for the biceps brachii (Moritani and DeVries, 1978), muscles of the shoulder (Laursen et al., 1998), and first dorsal interosseus muscle of the hand (Milner-Brown and Stein, 1975). Multiple linear regression models were used to predict forces from the three sets of NEMG measures. Although the high levels of predictive accuracy supported the linearity assumption, further work is needed to verify this observation.

Based on the procedures implemented in this study, future research is needed to create a prediction process that is easy to implement for an industrial practitioner. In some way the process would have to be automated. Data based on finger strength must be collected and regression models generated for each individual and coupling. After the collection of real-time data, further calculations must be performed in order to determine the force requirements, including filtering and normalization of EMG measures. The intention of this research was to create simple regression models. A means for simplifying the procedure would be to reduce the number of predictor variables within the multiple linear regression models. This would require only one set of NEMG levels. Depending on the application, however, the reduction in predictive accuracy may not be acceptable.

At this time regression models must be generated for each individual and each specific exertion. The creation of regression models for groups of individuals or similar exertions would reduce the necessary measurements and expand the versatility of the procedures. Such general models, however, may not be feasible given the extent of variability associated with different tasks and individual muscle recruitment, physiology, and geometry.

6. CONCLUSIONS

This study was motivated by the need to determine the force requirements of the fingers in a variety of tasks (couplings) and by the lack of such data in the literature. The frequent occurrence of upper limb injuries and musculoskeletal disorders has recently motivated research concerning the identification of risk factors and modifications to tools and workstations. Minimizing the percentage of hand and finger strength that is required to perform a task has been investigated as a means to reducing the risk of cumulative trauma disorders and other musculoskeletal disorders. The experiment determined the relationship between forces produced by the hand and fingers and NEMG data of muscles within the forearm. Accurate regression models were developed to predict finger forces from NEMG measures, thus providing useful data for design and task evaluation.

When direct measurement of finger forces is difficult or impossible, predictive models provide estimates of forces. This research derived models to predict finger forces during basic hand exertions from standardized electromyographic data of the forearm. The results suggest that standardized procedures for obtaining EMG data can be used to accurately predict finger forces.

REFERENCES

- Armstrong, T. J. (1986a). Ergonomics and cumulative trauma disorders. Hand Clinics, 2(3), 553-565.
- Armstrong, T. J. (1986b). Repetitive trauma disorders: job evaluation and design. Human Factors, 28(3), 325-336.
- Armstrong, T. J., Foulke, J. A., Joseph, B. S., and Goldstein, S. A. (1982). Investigation of cumulative trauma disorders in a poultry processing plant. American Industrial Hygiene Association Journal, 43(2), 103-116.
- Berg, V. J., Clay, D. J., Fathallah, F. A., and Higginbotham, V. L. (1988). The effects of instruction on finger strength measurements: applicability of the Caldwell Regimen. In F. Aghazadeh (Ed.), Trends in Ergonomics/Human Factors V (pp. 191-198). North-Holland: Elsevier Science.
- Buchanan, T. S., Moniz, M. J., Dewald, J. P. A., and Rymer, W. Z. (1993). Estimation of muscle forces about the wrist joint during isometric tasks using an EMG coefficient method. Journal of Biomechanics, 26(4/5), 547-560.
- Bureau of Labor Statistics. (1999). Bureau of Labor Statistics Safety and Health Statistics.
- Caldwell, L. S., Chaffin, D. B., Dukes-Dobos, F. N., Kroemer, K. H. E., Laubach, L. L., Snook, S. H., and Wasserman, D. E. (1974). A proposed standard procedure for static muscle strength testing. American Industrial Hygiene Association Journal, 35, 201-206.
- Chaffin, D. B., Herrin, G. D., Keyserling, W. M., and Foulke, J. A. (1977). Preemployment Strength Testing. Cincinnati: Technical Report No. 77-163 of the National Institute for Occupational Safety and Health.
- Cheverud, J., Gordon, C. C., Walker, R. A., Jacquish, C., Kohn, L., Moore, A., and Yamashita, N. (1990). 1988 Anthropometric Survey of U. S. Army Personnel. (Technical Reports 90/031 through 036 ed.). Natick, MA: U.S. Army Natick Research, Development, and Engineering Center.
- Clancy, E. A., and Hogan, N. (1991). Estimation of joint torque from the surface EMG. Neuromuscular Systems, 25, 877-888.

- Dempsey, P. G., and Ayoub, M. M. (1996). The influence of gender, grasp type, pinch width and wrist position on sustained pinch strength. International Journal of Industrial Ergonomics, 17, 259-273.
- Dowling, J. J. (1997). The use of electromyography for the noninvasive prediction of muscle forces. Sports Medicine, 24(2), 82-96.
- Fess, E. E., and Moran, C. (Eds.). (1981). American Society of Hand Therapists: Clinical Assessment Recommendations. Garner: the Society.
- Granata, K. P., and Marras, W. S. (1993). An EMG-assisted model of loads on the lumbar spine during asymmetric trunk extensions. Journal of Biomechanics, 26(12), 1429-1438.
- Granata, K. P., and Marras, W. S. (1995). An EMG-assisted model of trunk loading during free-dynamic lifting. Journal of Biomechanics, 28(11), 1309-1317.
- Grant, K. A., Habes, D. J., and Putz-Anderson, V. (1994). Psychophysical and EMG correlates of force exertion in manual work. International Journal of Industrial Ergonomics, 13, 31-39.
- Hallbeck, M. S., Rice, V. J. B., Fathallah, F. A., and Williams, V. H. (1989). Relationship between hand anthropometry and maximal pinch force. In A. Mital (Ed.), Advances in Occupational Ergonomics and Safety (pp. 507-513). Cincinnati, OH: Taylor & Francis.
- Hughes, R. E., and Chaffin, D. B. (1997). Using principal-components regression to stabilize EMG-muscle force parameter estimates of torso muscles. IEEE Transactions on Biomedical Engineering, 44(7), 639-642.
- Hughes, R. E., Chaffin, D. B., Lavender, S. A., and Andersson, G. B. J. (1994). Evaluation of muscle force prediction models of the lumbar trunk using surface electromyography. Journal of Orthopaedic Research, 12(5), 689-698.
- Imrhan, S. N. (1989). Trends in finger pinch strength in children, adults, and the elderly. Human Factors, 31(6), 689-701.
- Imrhan, S. N., and Rahman, R. (1995). The effects of pinch width on pinch strengths of adult males using realistic pinch-handle coupling. International Journal of Industrial Ergonomics, 16, 123-134.

- Jacobson, C., and Sperling, L. (1976). Classification of the hand-grip. Journal of Occupational Medicine, 18(6), 395-398.
- Kinoshita, H., Kawai, S., Ikuta, K., and Teraoka, T. (1996). Individual finger forces acting on a grasped object during shaking actions. Ergonomics, 39(2), 243-256.
- Kroemer, K. H. E. (1986). Coupling the hand with the handle: an improved notation of touch, grip, and grasp. Human Factors, 28(3), 337-339.
- Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E. (1990). Engineering Physiology: Bases of Ergonomics. (2nd ed.). New York: Van Nostrand Reinhold.
- Laubach, L. L., and McConville, J. T. (1969). The relationship of strength to body size and typology. Medicine and Science in Sports, 1, 189-194.
- Laursen, B., Jensen, B. R., Nemeth, G., and Sjogaard, G. (1998). A model predicting individual shoulder muscle forces based on relationship between electromyographic and 3D external forces in static position. Journal of Biomechanics, 31, 731-739.
- Marras, W. S. (1990). Industrial electromyography (EMG). International Journal of Industrial Ergonomics, 6, 89-93.
- Mathiowetz, V., Kashman, N., Volland, G., Weber, K., Dowe, M., and Rogers, S. (1985a). Grip and pinch strength: normative data for adults. Archives of Physical Medicine and Rehabilitation, 66, 69-74.
- Mathiowetz, V., Rennells, C., and Donahoe, L. (1985b). Effect of elbow position on grip and key pinch strength. Journal of Hand Surgery, 10(A), 694-697.
- Mathiowetz, V., Weber, K., Volland, G., and Kashman, N. (1984). Reliability and validity of grip and pinch strength evaluations. Journal of Hand Surgery, 9(A), 222-226.
- McGill, S. M. (1992). A myoelectrically based dynamic three-dimensional model to predict loads on lumbar spine tissues during lateral bending. Journal of Biomechanics, 25(4), 395-414.
- Milner-Brown, H. S., and Stein, R. B. (1975). The relation between the surface electromyogram and muscular force. Journal of Physiology, 246, 549-569.

- Moritani, T., and DeVries, H. (1978). Reexamination of the relationship between the surface integrated electromyogram (IEMG) and force of isometric contraction. American Journal of Physical Medicine, 57(6), 263-277.
- Napier, J. R. (1956). The prehensile movements of the human hand. Journal of Bone and Joint Surgery, 38B(4), 902-913.
- Neter, J., Kutner, M. H., Nachtsheim, C. J., and Wasserman, W. (1996). Applied Linear Statistical Models. (4th ed.). Chicago: McGraw-Hill Companies.
- Nussbaum, M. A., Chaffin, D. B., and Martin, B. J. (1995). A back-propagation neural network model of lumbar muscle recruitment during moderate static exertions. Journal of Biomechanics, 28(9), 1015-1024.
- Palanisami, P., Narasimhan, T. M., and Fernandez, J. E. (1994). The effect of sitting on peak pinch strength. In F. Aghazadeh (Ed.), Advances in Industrial Ergonomics and Safety VI (pp. 587-594). New York: Taylor & Francis.
- Perry, J., and Bekey, G. A. (1981). EMG-force relationships in skeletal muscle. CRC Critical Reviews in Biomedical Engineering, Dec, 1-22.
- Radwin, R. G., Oh, S., Jensen, T. R., and Webster, J. G. (1992). External finger forces in submaximal five-finger static pinch prehension. Ergonomics, 35(3), 275-288.
- Raftery, A. E., Madigan, D., and Hoeting, J. A. (1997). Bayesian model averaging for linear regression models. Journal of the American Statistical Association, 92(437), 179.
- Ray, G. C., and Guha, S. K. (1983). Relationship between the surface emg and muscular force. Medical and Biological Engineering and Computing, 21(September), 579-586.
- Rice, V. J., Williamson, T. L., and Sharp, M. (1998). Using anthropometry and strength values to predict grip strength. In S. Kumar (Ed.), Advances in Occupational Ergonomics and Safety (pp. 378-381). Amsterdam: IOS Press.
- Roebuck, J. A., Kroemer, K. H. E., and Thomson, W. G. (1975). Engineering Anthropometry Methods. New York: Wiley.
- Schmidt, R. T., and Toews, J. V. (1970). Grip strength as measured by the Jamar dynamometer. Archives of Physical Medicine & Rehabilitation, June, 321-327.

- Solomonow, M., Baratta, R., Shoji, H., and D'Ambrosia, R. (1990). The EMG-force relationships of skeletal muscle: dependent on contraction rate, and motor units control strategy. Electromyographic Clinical Neurophysiology, 30, 141-52.
- Sommerich, C. M., Marras, W. S., and Parnianpour, M. (1998). A method for developing biomechanical profiles of hand-intensive tasks. Clinical Biomechanics, 13, 261-271.
- Stobbe, T. J. (1982). The development of a practical strength testing program in industry. Unpublished Ph.D. dissertation, University of Michigan, Ann Arbor, Michigan.
- Stokes, I. A. F., Moffroid, M., Rush, S., and Haugh, L. D. (1989). EMG to torque relationship in rectus abdominis muscle. Spine, 14(8), 857-61.
- Stokes, I. A. F., Rush, S., Moffroid, M., Johnson, G. B., and Haugh, L. D. (1987). Trunk extensor EMG - torque relationship. Spine, 12(8), 770-776.
- Swanson, A. B., Matev, I. B., and de Groot, G. (1970). The strength of the hand. Bulletin of Prosthetics Research, Fall, 145-153.
- Webb Associates. (1978). Vol I, NASA Ref. 1024, Anthropometric Source Book (pp. Chapter VI & VII): National Aeronautics and Space Administration.
- Williamson, T. L., and Rice, V. J. (1992). Re-evaluation of the Caldwell Regimen: the effect of instruction on handgrip strength in men and women. In S. Kumar (Ed.), Advances in Industrial Ergonomics and Safety IV (pp. 675-682). New York: Taylor & Francis.
- Woods, J. J., and Bigland-Ritchie, B. (1983). Linear and non-linear surface EMG/force relationships in human muscles: An anatomical/functional argument for the existence of both. American Journal of Physical Medicine, 62(6), 287-299.
- Wyss, U. P., and Pollak, V. A. (1984). Surface electromyogram (EMG)/muscle force: a muscle model based on RMG peaks. Engineering in Medicine, 13(1), 27-33.
- Zipp, P. (1982). Recommendations for the standardization of lead positions in surface electromyography. European Journal of Applied Physiology, 50, 41-54.
- Zuniga, E. N., and Simons, D. G. (1969). Nonlinear relationship between averaged electromyogram potential and muscle tension in normal subjects. Archives of Physical Medicine and Rehabilitation, Nov, 613-20.

VITA

ANGELA DIDOMENICO ASTIN (*Finger force capability: measurement and prediction using anthropometric and myoelectric measures*) was born on July 20, 1970, in New Haven, Connecticut. She received her Bachelor of Arts in Mathematics from the University of Connecticut in May 1992. In 1993, after spending fifteen months working at the University of Connecticut's School of Business and Real Estate Center, Ms. Astin decided to return to school to pursue a graduate degree in Mathematics. Studying mathematics provided Ms. Astin the opportunity to teach other students, both in the classroom and individually. She received her Master of Science in Mathematics from Virginia Polytechnic Institute and State University in May 1996. While concluding her mathematics requirements, she discovered Human Factors Engineering and joined the Industrial and Systems Engineering Department. After a year as a teaching assistant for Work Design (ISE 3624) and Work Physiology (ISE 4624), The National Institute for Occupational Safety and Health funded her master's research in the Industrial Ergonomics Laboratory. She is currently an active member of the Human Factors and Ergonomics Society (Secretary), American Society of Safety Engineers (President), and Alpha Pi Mu.