FACTORS AFFECTING APPLIED GRIP FORCE AND A SYSTEM FOR CLASSIFYING THE FORCEFUL ASPECTS OF MANUAL WORK

by

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CHAPTER 1

INTRODUCTION

1.1 Thesis Statement

The grip force requirements of some manual tasks are affected by object weight, work pace, the hand/object coefficient of friction (COF), and grip/pinch strength. The COF effect on pinch force is load-dependent. A taxonomy of the forceful elements of manual tasks can be created that could serve as a framework for development of a standard data system for determining the force requirements of manual work.

1.2 Research Objectives

To evaluate the above theses, the following research objectives were established:

a) To determine the effect on grip/pinch force of object weight, hand/object coefficient of friction (COF), work pace, and grip strength.

b) To determine if the COF effect on pinch force is load-dependent.

c) To develop a taxonomy for describing and classifying the forceful aspects of manual work.

1.3 Rationale

Forceful manual exertion is a risk factor for cumulative trauma disorders (CTDs) such as tenosynovitis and carpal tunnel syndrome (e.g., Thompson, Plewes and Shaw 1951; Smith, Sonstegard and Anderson 1977; Armstrong and Chaffin 1979; Falck and Aarnio 1983; Silverstein, Fine and Armstrong 1986). CTDs are painful and disabling, often resulting in lost income and decreased productivity (Maeser, Hayes, and Hyde 1986; Hymovich and Lyndholm 1966; Wisseman and Badger 1977; Browne, Nolan and Faithfull 1984; Jensen, Klein and Sanderson 1983). Although force is associated with the development of CTDs, it is seldom measured or clearly defined. Most descriptions of force are qualitative, e.g., "unusually heavy manual work" (Thompson et al. 1951), "forceful flexion of the fingers" (Tanzer 1959), and "prolonged heavy grasping" (Falck and Aarnio 1983). Consequently, the amount of force that constitutes excessive risk is unknown. One reason more studies have not been done in this area is because grip force in manual work is not easily measured.

Determinants of required grip force are 1) the laws of mechanics (inertia, acceleration, and reaction), 2) the laws of static friction, and 3) physiological responses to environmental stimuli. The amount of force exerted, however, is a function not only of these three factors but of anatomical, behavioral, and physiological responses as well. Physiological responses are manifested 1) by their effect on an individual's perception of required grip force (low temperatures, for example) (e.g., Flatt 1961; Mills 1957; 2) by causing a mechanical affect (e.g., a reduced coefficient of friction due to dry hands) (Coomaish and Bottoms 1971); and 3) by causing disturbances in neuromuscular control resulting in involuntary muscle contraction (e.g., tool recoil and segmental vibration) (e.g., Carlsoo and Mayr 1974; Radwin, VanBergeijk, and Armstrong 1989).

The focus of recent studies of hand force has been on measuring the effect of selected factors such as load, vibration, handle shape, tool torque, and surface frictional conditions on hand force (e.g., Farkkila, Pyykko, Korhonen, and Starck 1979; Westling and Johansson 1984; Johnson 1988; Radwin and Armstrong 1987; Radwin, VanBergeijk, and Armstrong 1989; Lyman and Groth 1958). In general, these studies examined whether statistically different amounts of force were exerted for various experimental conditions.

Other investigators have characterized hand force categorically in an attempt to measure the association between exposure and the development of CTDs (e.g., Silverstein, Fine and Armstrong 1986).

Although sporadic studies have measured the effect of selected factors on hand force, no systematic effort has been made to compile these data or collect additional data in a format for determining the force requirement of manual tasks. Few quantitative force data exist, and existing data have not been compiled or organized into a format for determining the force requirements of manual tasks.

The long-range goal of this research is to establish a foundation for the development of a methodology for estimating the hand force requirements of manual work based on task characteristics and individual traits. Such a system would provide a means to identify, quantify, and ultimately control forceful components of work through job design. Quantification of force should provide insight into the pathomechanics of CTDs as it relates to dose-response. Such goals are important in the promotion of worker safety, health and productivity. The proposed system also lends itself to prosthetics research, design and evaluation in terms of estimating the force required to perform manual tasks associated with daily living.

1.4 Dissertation Organization

This dissertation is presented as three related papers; each in a separate chapter. Chapter 2 presents two laboratory experiments that evaluated the effect of friction, weight, work pace, gender, and hand strength on pinch and grip force. In Chapter 3, results are presented of a third laboratory experiment evaluating the effect of friction on pinch force under near maximal load conditions. The latter study was designed to answer questions arising from Chapter 2. Chapter 4 describes a taxonomy for classifying the forceful elements of manual work; Chapter 5 integrates the research presented in the previous three chapters.

CHAPTER 2

THE EFFECTS OF LOAD, PACE, AND FRICTION ON PINCH AND GRIP FORCE

2.1 Abstract

This study examined the influence of load, coefficient of friction (COF), work pace, gender, and grip/pinch strength on the amount of grip/pinch force used to perform a simple, repetitive manual task. Two laboratory experiments were conducted, one for each of two hand postures: pinch and power grip. Seventy-two university students, balanced for gender, participated in each study. Dependent variables were *peak*, *mid-cycle*, and *mean* grip/pinch force. Predictive models were developed using forward stepwise regression. Load was the most powerful predictor explaining from 9% to 25% of the variation in pinch and grip force. The load-strength interaction was the most significant predictor according to the stepwise procedure, but it accounted for only 2% to 7% more variation than load alone.

The results of this study indicate that a combination of variables representing personal and task factors can be

identified that explain significant amounts of variation in pinch and grip force performance data. The majority of the variation in performance data remains to be explained, however. The models developed provide insight into the roles of the selected factors on pinch and grip force and the extent of their effects. The results of this study are useful for job analyses, tool design, and for the design of future research concerning the force requirements of manual tasks.

2.2. Introduction

Forceful, repetitive exertion is a risk factor for cumulative trauma disorders (CTDs) such as tenosynovitis and carpal tunnel syndrome (e.g., Thompson, Plewes and Shaw 1951; Smith, Sonstegard and Anderson 1977; Armstrong and Chaffin 1979; Falck and Aarnio 1983; Silverstein, Fine and Armstrong 1986). CTDs are painful and disabling, often resulting in lost income and decreased productivity (Maeser, Hayes, and Hyde 1986; Hymovich and Lyndholm 1966; Wisseman and Badger 1977; Browne, Nolan and Faithfull 1984; Jensen, Klein and Sanderson 1983).

Although force is frequently associated with CTDs, it is seldom measured or clearly defined. Most descriptions of force are qualitative, e.g., "unusually heavy manual work" (Thompson et al. 1951), "forceful flexion of the fingers"

(Tanzer 1959), and "prolonged heavy grasping" (Falck and Aarnio 1983). One reason for the lack of quantitative data is that measuring the hand force used in manual tasks is technically challenging.

Electromyography (EMG) of the finger flexor and/or extensor muscles of the forearm has been used to estimate hand force (Armstrong, Foulke, Joseph, and Goldstein 1982; Arndt 1987; Silverstein, Fine and Armstrong 1987; Lyman and Groth 1958; Radwin and Armstrong 1987). This approach is based on the empirical relationship between the electrical activity of muscle and hand force when the exertion is submaximal, isometric, and of short duration (e.g., DeVries 1968; Inman et al. 1952; Basmajian and Deluca 1985). With uncontrolled, dynamic motions, however, the signal is influenced by factors such as muscle length, muscle velocity, and motion artifact which confound interpretation (Basmajian and Deluca 1985; Petrofsky and Phillips 1983).

Another technique for measuring manual force (i.e., grip compression force) is by strain gages placed in tools or test devices (Lyman and Groth 1958; Farkkila, Pyykko, Korhonen, and Starck 1979; Radwin and Armstrong 1987; Radwin, VanBergeijk, and Armstrong 1989). Tool instrumentation requires special technical skills, however, and not all tools are amenable to such modification. Because the equipment needed to implement this technique may

be intrusive in the work place, it usually is used under controlled laboratory conditions.

In some cases, hand force has been estimated with mathematical models (Armstrong 1985; Pheasant and O'Neill 1976). Armstrong (1985), for example, suggested that Amonton's Law (Friction Force = Normal Contact Force * COF) (Bowden and Tabor 1986) could be used to estimate required pinch force for static tasks. Accordingly, when the hand/object coupling is frictional, required pinch force is directly proportional to object weight and inversely proportional to the hand/object coefficient of friction (COF), Fpinch = Weight/(2*COF).

The effects of selected tool and task factors on the amount of hand force used have been measured in the laboratory using both EMG and strain gage instrumented devices. Westling and Johansson (1984), for example, used a strain gage device to evaluate the effects of object weight (0.1 N - 10 N) and the hand/object COF on the amount of pinch force used for a precision holding task. Although the effects were not tested for statistical reliability, the authors reported an "approximately linear" relationship between pinch force and object weight - a conclusion that was evident from their graphs. The slope of the weight - pinch force relationship was inversely proportional to the COF of the surface, i.e., the more slippery the surface, the

steeper the slope. Similarly, Johnson (1988) reported that subjects used significantly (16%) less grip force to operate a powered screwdriver when a high-friction (vinyl-covered) handle was placed over a standard low-friction (aluminum) handle. These results support the findings of Westling and Johansson (1984) and Buchholz *et al.* (1988) that exerted force and COF are inversely related.

Lyman and Groth (1958) measured the effect (using a strain gage device) of four task factors on pinch force exertion: load, distance moved, direction moved, and protective handcovering. All main effects, except direction moved, were significant. Load was the most important variable accounting for pinch force. Other task factors reported to affect manual exertion are tool size and shape (Kahlil 1973; Ayoub and LoPresti 1971; Cochran and Riley 1986; Johnson 1988), and work rate (Arndt 1987; Lundervold 1951). Faster work rates, for example, have been associated with increased EMG activity (e.g., Laville 1968; Arndt 1987; Lundervold 1951). Also, in a pilot study for the present experiments, significantly higher grip compression forces (using a strain gage device) were found at the fast pace (60 cycles/minute) vs the slow pace (i.e., 40 CPM). The effect of personal characteristics such as gender and strength on exerted force were not found in the research literature.

The long-range goal of this research is to establish a foundation for the development of a methodology for estimating the hand force requirements of manual work based on task characteristics and individual traits. The purpose of this study was to evaluate the effects of selected task factors (load, COF, pace) and hand strength on the grip and pinch force exerted during a simple, repetitive manual task.

2.3 Materials and Methods

Two experiments were performed, one for each of two hand postures: pinch and power grip. These studies are referred to below as the **Pinch Study** and the **Grip Study**. Experimental conditions were designed to simulate a simple, repetitive manual task.

2.3.1 *Subjects*

Seventy-two university students, balanced for gender, participated in each study. Criteria for participation were absence of signs or symptoms of impaired tactile sensitivity (e.g., numbness, tingling, trauma or surgery), and no recent involvement in an activity that could temporarily diminish tactile sensitivity such as hand ball, hammering, or exposure to vibrating hand tools. Mean ages (± SD) were 20 (± 2) and 22 (± 6) for the Pinch and Grip Study, respectively. The experiments were reviewed and conducted in accordance with the National Institute for Occupational

Safety and Health (NIOSH) Human Subjects Review Board procedures. Informed consent was obtained. Subjects either were paid for their participation or received course credit.

2.3.2 *Apparatus*

Studies were performed in a laboratory with ambient temperatures between 75-77°F. Grip/pinch force was measured by one of two strain gage devices (Pronk and Niesing 1981): a 2.5-cm cube for the Pinch Study and an elliptical cylinder for the Grip Study - that could accommodate different loads and surface coverings (Fig. 2.1). Strain gage signals were amplified and collected at 20 Hz on a microcomputer using a 12-bit analog-to-digital converter and commercial data acquisition software.

2.3.3 *Procedure*

To prepare the skin, subjects cleansed their hands with a disposable, moist paper towelette. The experimenter demonstrated the task and explained the experimental procedure to each subject. For the Pinch and Grip Study, respectively, the workstation was adjusted to 7.5 cm or 12.5 cm below the tip of the olecranon, with the elbow bent at 90 degrees (Fig. 2.1). Subjects stood with their dominant hand in line with the center of the workstation and used this hand to move the test device between two targets in time with a metronome. Subjects practiced the task until they appeared to the investigator to be familiar with the

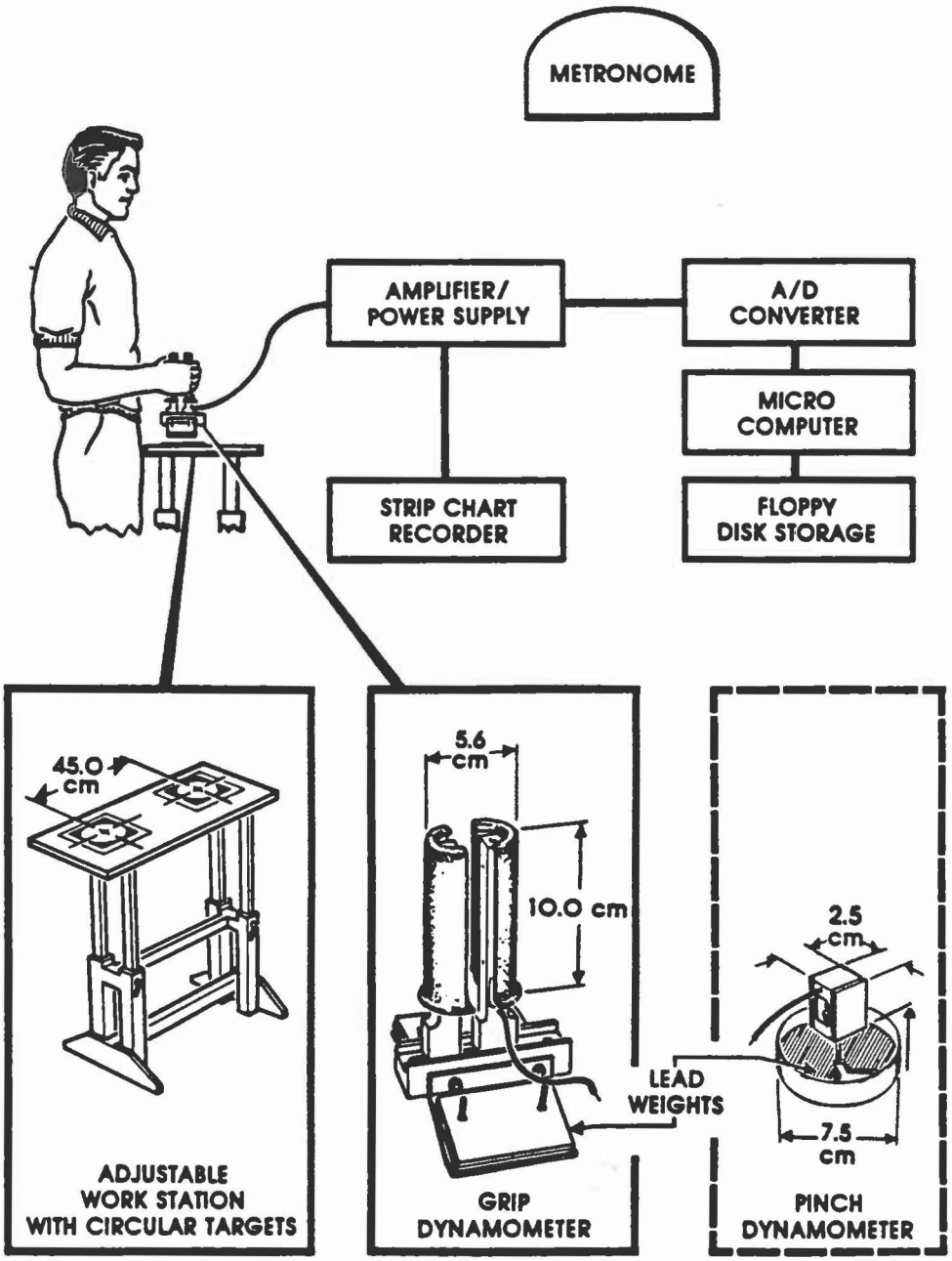

Figure 2.1 Experimental apparatus and setup.

equipment and the task, and they could coordinate their movements with the metronome.

For the Grip Study, a power grip (full hand wrapped around the oblong test object) was used (Fig. 2.1). In the Pinch Study, the object was held between the pads of the index and middle fingers, and the thumb. Subjects performed three 40-second trials, each followed by a one-minute rest period. After the last trial, and following a two-minute rest period, the extra weights were removed and maximum grip/pinch strength was measured. Three maximal exertions were performed, each followed by a one-minute rest period. Strength was computed by averaging the peak force for each trial.

2.3.4 *Experimental design and analysis*

Two completely randomized 3 X 3 X 2 X 2 (load X COF X pace X gender) experiments were designed to investigate the effect of these variables on pinch and grip force. Three loads were used in each experiment: 3.5, 6.1, and 8.6 N for the Pinch Study; 6.4, 13.0, and 19.8 N for the Grip Study. The highest load was selected from a pilot study to determine the maximum weight the weakest subjects could move comfortably under experimental conditions. The lowest load used was equivalent to the weight of the empty test device; the middle load was midway between these extremes. Each study used three frictional surfaces (COFs). The Pinch

Study used the following materials: polished aluminum (mean COF = 0.33 ± 0.09), smooth, shiny vinyl (0.56 ± 0.15), and 320 grit sandpaper (0.66 ± 0.11) [cf Buchholz, Frederick and Armstrong 1988]. The same low and high friction materials were used for the Grip Study, whereas the medium frictional surface was textured vinyl (COF = 0.50 ± 0.12). Materials were selected to represent the surface frictional characteristics of objects commonly found in the work place (metal and vinyl) and to maximize differences in friction.

Paces were 60 and 40 CPM for the Pinch Study; 54 and 36 CPM for the Grip Study. These rates represented 105% and 70% of normal performance levels as established by the MTM (Methods-Time Measurement) system for the task conditions (Smith 1978). The motion was an MTM "C" Move, i.e., the object was moved (45 cm) to an exact location.

Three dependent variables were selected to characterize pinch and grip force for each cycle: *peak*, *midcycle*, and *mean* (Fig. 2.2). *Peak* force was the maximum force during the cycle; *mean* force was the arithmetic average of the non-zero data points. *Midcycle* was defined as the midpoint of the time when the test device was in transit (i.e., the midpoint of the non-zero data points). A summary score for each of the three dependent variables was computed for each subject by averaging the force values of the middle 15 cycles of the last two of three trials.

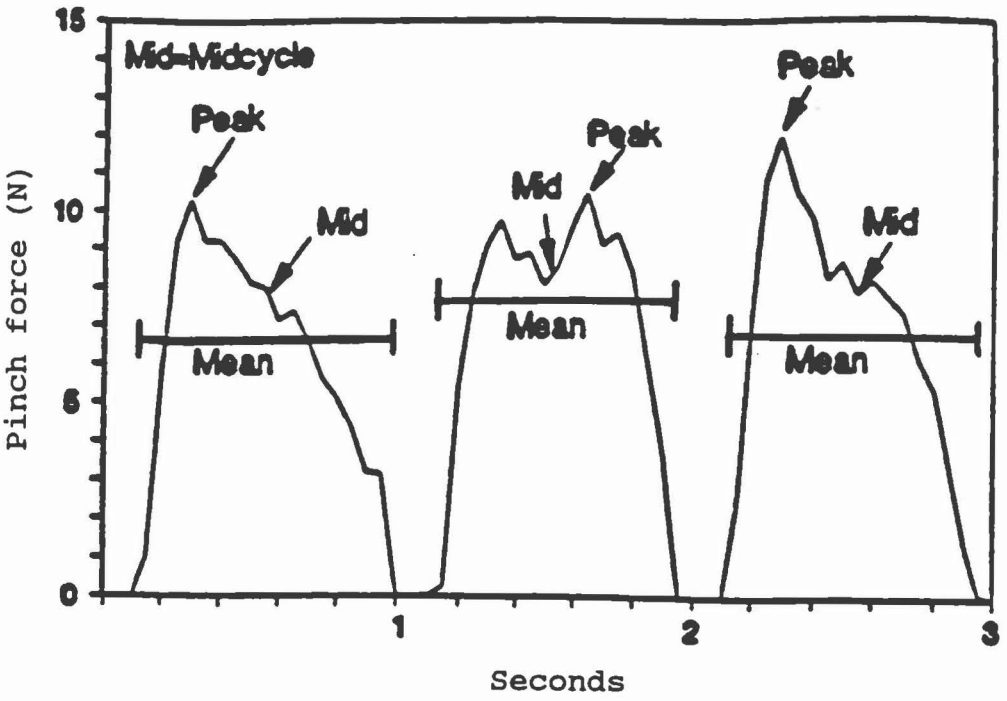

Figure 2.2 Three representative cycles showing *mean*, *midcycle*, and *peak* pinch force (fast pace, 3.5 N sandpaper).

Forward-stepwise regression was used to build models for pinch and grip force using load, COF, pace, gender, grip/pinch strength, and all two-way interactions (SAS Institute 1985; Draper and Smith 1981). Pace was characterized as 1 = Slow, 0 = Fast; Gender as 1 = Male, 0 = Female. Strength was entered as a covariate. The difference between the means of the three dependent variables were compared using paired t-tests. To determine if "overgripping" was a function of load force, the mean grip/pinch force to load force ratio (GF:LF and PF:LF) for each experimental load was computed, and then compared using linear regression.

2.4 Results

2.4.1 *Grip study*

The *mean*, *midcycle*, and *peak* grip forces for each experimental condition, by gender, are presented in Tables 2.1 - 2.3. Individual *mean* grip forces ranged from 3.9 to 90.7 N; *midcycle* forces ranged from 4.1 to 108.3 N; and *peak* forces ranged from 7.1 to 144.8 N. Increasing load by 209% (from 6.4 to 19.8) resulted in a 118% increase in *mean* grip force (19.0 to 41.4 N); a 116% increase in *midcycle* force (22.5 to 48.6 N); and a 129% increase in *peak* force (30.4 to 69.5 N).

Table 2.1: *Mean* grip force (N) for each experimental condition (mean ± SD).

COF		6.4 N	13.0 N	19.8 N	Pooled
0.33	Fast				
	F	15.4 ± 6.3	31.6 ± 14.5	48.3 ± 14.0	
	M	23.8 ± 14.2	23.6 ± 17.5	57.3 ± 8.9	
	Slow				
	F	36.9 ± 33.6	17.3 ± 2.7	36.7 ± 3.3	
	M	22.0 ± 9.4	22.0 ± 7.8	56.2 ± 12.8	
	Pooled	24.5 ± 16.7	23.6 ± 10.7	49.6 ± 11.9	32.6 ± 17.7
0.50	Fast				
	F	4.4 ± 0.7	28.7 ± 8.1	45.6 ± 27.1	
	M	24.5 ± 17.7	48.5 ± 39.8	44.1 ± 2.0	
	Slow				
	F	9.8 ± 0.6	13.7 ± 4.2	18.8 ± 5.8	
	M	10.7 ± 8.4	51.3 ± 55.9	39.1 ± 10.3	
	Pooled	12.4 ± 10.9	35.5 ± 30.9	36.9 ± 16.0	28.3 ± 23.3
0.66	Fast				
	F	21.1 ± 20.8	29.5 ± 15.0	40.8 ± 19.6	
	M	14.7 ± 4.4	21.0 ± 7.3	46.2 ± 18.4	
	Slow				
	F	22.1 ± 3.7	13.0 ± 3.3	24.3 ± 3.1	
	M	22.2 ± 22.7	13.7 ± 4.5	39.8 ± 2.1	
	Pooled	20.0 ± 12.3	19.3 ± 9.8	37.8 ± 13.5	25.7 ± 14.4
Pooled		19.0 ± 13.9	26.2 ± 20.1	41.4 ± 14.6	
				Grand average	28.9 ± 18.7

Newtons rounded to nearest tenth. F = female, M = male.

Table 2.2: *Midcycle* grip force (N) for each experimental condition (mean ± SD).

COF		6.4 N	13.0 N	19.8 N	Pooled
0.33	Fast				
	F	15.3 ± 7.3	38.1 ± 20.9	71.4 ± 36.8	
	M	28.6 ± 17.5	28.1 ± 21.8	61.1 ± 17.0	
	Slow				
	F	46.7 ± 44.2	18.4 ± 3.7	41.4 ± 6.9	
	M	25.7 ± 12.8	23.4 ± 6.4	67.6 ± 13.2	
	Pooled	29.1 ± 22.4	27.0 ± 14.1	60.4 ± 20.1	38.8 ± 24.2
0.50	Fast				
	F	4.5 ± 0.5	32.6 ± 10.3	58.4 ± 42.7	
	M	30.6 ± 25.5	54.4 ± 43.2	48.3 ± 6.2	
	Slow				
	F	10.9 ± 1.2	14.6 ± 4.5	21.3 ± 6.3	
	M	11.8 ± 9.6	60.9 ± 67.1	48.5 ± 15.7	
	Pooled	14.4 ± 14.6	40.6 ± 36.2	44.1 ± 22.9	33.1 ± 28.4
0.66	Fast				
	F	24.4 ± 26.1	34.1 ± 20.2	46.3 ± 25.2	
	M	15.2 ± 5.4	21.5 ± 8.3	43.2 ± 11.3	
	Slow				
	F	26.6 ± 1.9	14.3 ± 3.6	27.7 ± 2.1	
	M	29.9 ± 31.9	15.1 ± 6.9	47.9 ± 3.1	
	Pooled	24.0 ± 16.8	21.3 ± 12.2	41.3 ± 13.6	28.8 ± 16.4
Pooled		22.5 ± 18.5	29.6 ± 23.9	48.6 ± 20.4	
				Grand average	33.6 ± 23.5

Newtons rounded to nearest tenth. F = female, M = male.

Table 2.3: *Peak* grip force (N) for each experimental condition (mean ± SD).

COF		6.4 N	13.0 N	19.8 N	Pooled
0.33	Fast				
	F	24.9 ± 7.8	51.8 ± 21.9	88.0 ± 35.8	
	M	40.6 ± 21.3	36.4 ± 23.1	93.2 ± 0.1	
	Slow				
	F	57.8 ± 55.6	26.6 ± 3.3	59.3 ± 2.4	
	M	36.1 ± 15.0	36.6 ± 16.3	90.8 ± 32.6	
	Pooled	39.8 ± 26.6	37.8 ± 16.7	82.7 ± 23.3	53.5 ± 30.2
0.50	Fast				
	F	7.4 ± 0.5	46.4 ± 9.0	82.6 ± 38.6	
	M	36.1 ± 20.4	88.3 ± 80.0	73.9 ± 9.7	
	Slow				
	F	18.4 ± 3.0	25.9 ± 9.0	29.6 ± 11.7	
	M	18.4 ± 13.9	81.0 ± 86.0	61.4 ± 7.6	
	Pooled	20.1 ± 14.5	42.9 ± 40.4	61.8 ± 26.7	41.6 ± 32.9
0.66	Fast				
	F	32.7 ± 30.3	45.6 ± 20.2	63.8 ± 34.3	
	M	22.3 ± 6.0	34.0 ± 9.5	89.5 ± 41.2	
	Slow				
	F	26.6 ± 1.9	21.5 ± 6.1	39.5 ± 10.0	
	M	29.9 ± 31.9	20.7 ± 4.1	62.2 ± 5.7	
	Pooled	31.4 ± 18.8	30.4 ± 14.1	63.8 ± 28.1	41.9 ± 25.6
Pooled		30.5 ± 21.3	37.1 ± 25.8	69.5 ± 26.7	
				Grand average	45.7 ± 29.8

Newtons rounded to nearest tenth. F = female, M = male.

Across all experimental conditions, *peak* grip force was 65% greater than *mean* grip force, 47.6 N vs 28.8 N ($t = 11.4$, $p < .001$) and 42% greater than *midcycle* forces, 47.6 N vs 33.6 N ($t = 9.9$, $p < .001$). *Midcycle* force was 17% greater than *mean* force (33.6 N vs 28.8 N; $t = 6.1$, $p < .001$).

Maximum voluntary contraction grip strength (MVC) ranged from 268.5 N to 659.5 N (mean = 437.3, SD = 79.3) for men and from 156.8 N to 387.8 N (mean = 270.6, SD = 53.7) for women. The male subjects were significantly stronger than the female subjects ($t = 10.45$, $p < .001$). Depending on the experimental condition and the force measure, subjects used from 1% to 47% of their MVC to perform the task. Mean values for each load condition (averaged over 24 subjects) are presented in Table 2.4.

Guided by stepwise regression, models were developed for all measures of grip force (Table 2.5). The most significant predictor for *mean*, *midcycle*, and *peak* grip force was the load-strength interaction. The load effect was greatest for stronger subjects (Fig. 2.3). This interaction model explained 24% to 32% of the variation, depending on the force measure. Load, the most powerful single variable, explained 21% to 25% of the variation. Strength alone explained a small, but statistically

Table 2.4: Percent of maximum voluntary contraction strength (%MVC) used to perform task for *mean*, *midcycle*, and *peak* grip force by load.

	Percent MVC Grip Force (mean ± SD)		
Load (N)	*Mean*	*Midcycle*	*Peak*
6.4	6 ± 4	7 ± 6	9 ± 7
13.0	8 ± 5	9 ± 6	13 ± 8
19.8	12 ± 5	15 ± 7	21 ± 8

Table 2.5: Predictive models of grip force.

		RMSE	R^2
Mean			
Model I	Fg = 7.0 + 1.7(L)	16.4	0.24*
Model II	Fg = 12.3 + 0.05(S)	18.2	0.07*
Model III	Fg = - 9.4 + 1.7(L) + 0.05(S)	15.7	0.31*
Model IV	Fg = 10.0 + 0.004(L*S)	15.7	0.31*
Model V	Fg = 1.5 + 0.9(L) + 0.02(S) + 0.002(L*S)	15.8	0.32*
Midcycle			
Model I	Fg = 8.2 + 1.9(L)	21.1	0.21*
Model II	Fg = 16.1 + 0.05(S)	23.1	0.05
Model III	Fg = - 9.2 + 1.9(L) +0.05(S)	20.6	0.26*
Model IV	Fg = 12.7 + 0.005(L*S)	20.7	0.24*
Model V	Fg = - 6.1 + 1.7(L) + 0.04(S) + 0.06(L*S)	20.7	0.26*
Peak			
Model I	Fg = 9.6 + 2.9(L)	27.8	0.25*
Model II	Fg = 19.6 + 0.08(S)	31.0	0.07*
Model III	Fg = -18.2 + + 2.9(L) + 0.08(S)	26.7	0.32*
Model III	Fg = 14.7 + 0.007(L*S)	26.5	0.32*
Model IV	Fg = 7.7 + 1.07(L) + 0.006(S) + 0.005(L*S)	26.7	0.33*

RMSE = Root mean square error; Fg = grip force in Newtons (N); L = load (N), S = grip strength (N).
* Model significant at $p \leq .05$.

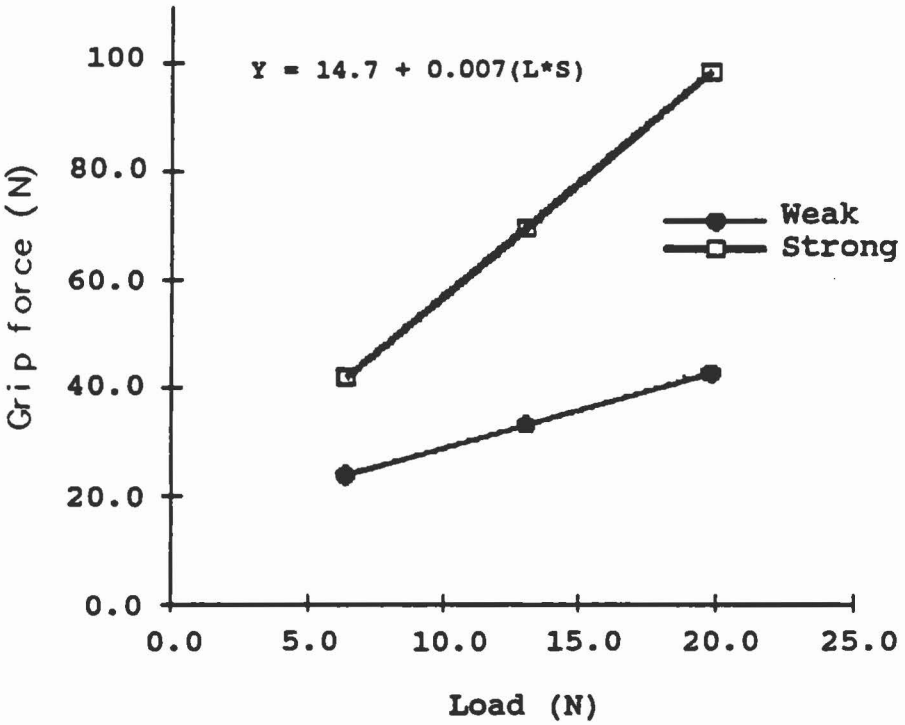

Figure 2.3 Load-strength interaction for *peak* grip force. L = Load, S = Strength 200 N, "weak" and 600 N, "strong"). [RMSE = 26.5 N]

significant amount (R^2 = .07, $p \leq .05$) of *mean* and *peak* grip force. A model with all main effects and two-way interactions explained 39%, 34%, and 42% of the variability for *mean*, *midcycle*, and *peak* grip force, respectively. No other variables were significant.

Grip force also was normalized to grip strength (%MVC) and models developed for this variable. The most significant predictors of normalized *mean* and *midcycle* force, as determined by the stepwise procedure, were load and the strength-COF interaction (Table 2.6). The COF effect was greatest for strong subjects (Fig. 2.4). The most significant predictors for normalized *peak* force were load, the strength-COF interaction, and the load-pace interaction. The load effect was greatest at the fast pace. Strength explained a small, but significant amount (R^2 = .05, $p \leq .05$). The ratio of grip force to load force (GF:LF), an indicator of "overgripping," was not related to load for any dependent variable ($p > .05$).

2.4.2 *Pinch study*

The *mean*, *midcycle* and *peak* pinch forces for each load X COF X pace X gender category are presented in Tables 2.7 - 2.9. Individual *mean* pinch forces ranged from 2.0 N to 23.2 N; *midcycle* forces ranged from 2.1 N to 30.9 N; and, *peak* forces ranged from 3.4 N to 37.0 N. Increasing the load 146% (3.5 N to 8.6 N) resulted in a 58% increase in *mean*

Table 2.6: Predictive models of %MVC grip force.

Model	RMSE	R^2
Mean		
Y = 5.61 + 0.51(L) - 0.02(S*COF)	4.53	0.33
Midcycle		
Y = 6.89 + 0.60(L) - 0.03(S*COF)	5.95	0.30
Peak		
Y = 9.15 + 1.00(L) - 0.27(L*P) - 0.04(S*COF)	7.28	0.39

P = Pace (Slow = 1, Fast = 0); COF: Al = 0.33, Vinyl = 0.50, Sandpaper = 0.66; S = Grip strength (N); L = Load (N).

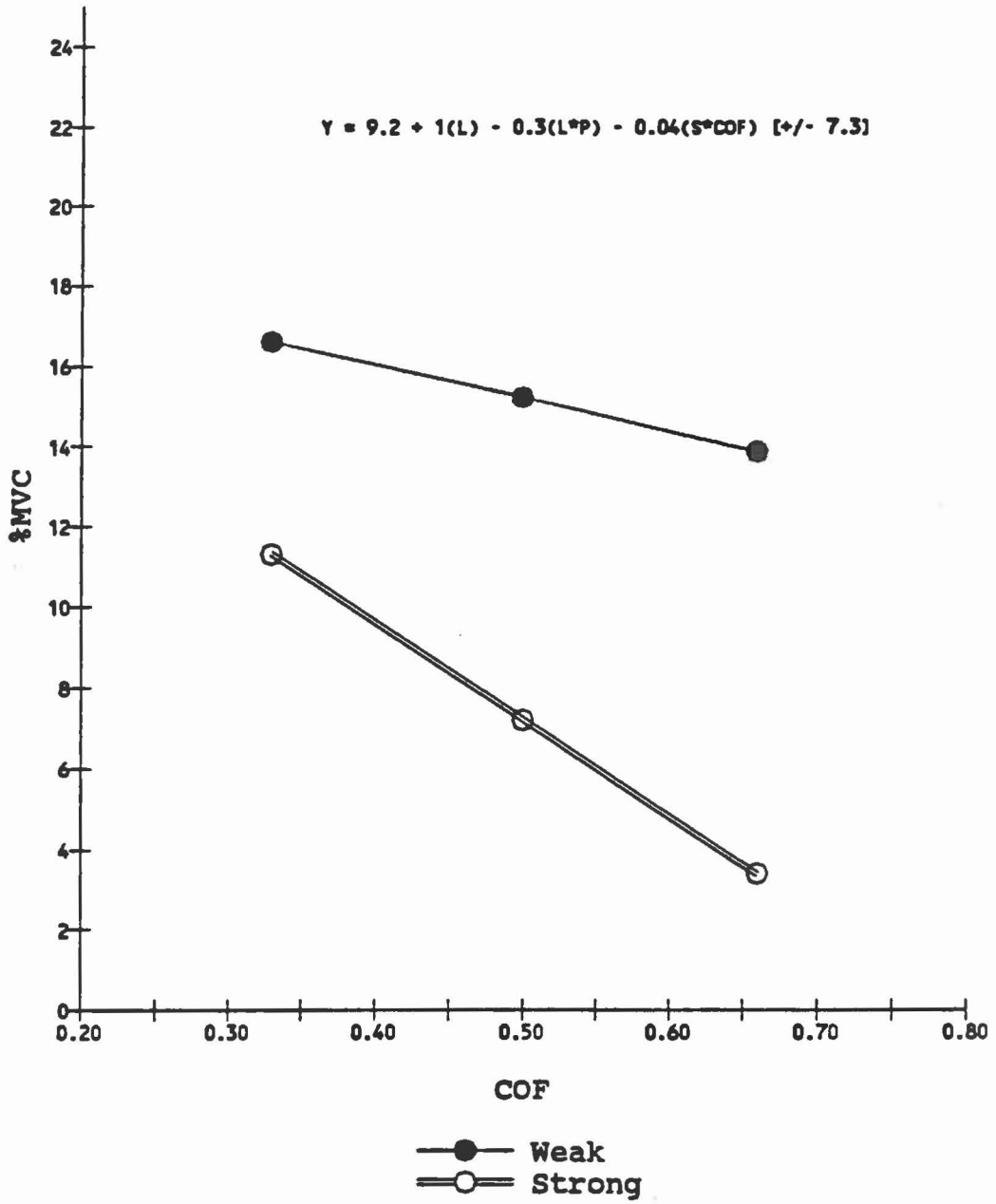

Figure 2.4 Strength-COF interaction for normalized *peak* grip force. Load = 10 N; Strength = 200 N "weak" and 600 N "strong;" Pace: 0 = Fast, 1 = Slow; COF = 0.33, 0.50, 0.66.

Table 2.7: *Mean* pinch force (N) for each experimental condition (mean ± SD).

COF		3.5 N	6.1 N	8.6 N	Pooled
0.33	Fast				
	F	6.5 ± 2.7	10.7 ± 3.0	11.9 ± 1.5	
	M	6.5 ± 0.4	8.6 ± 1.5	11.8 ± 1.9	
	Slow				
	F	8.0 ± 3.8	14.3 ± 9.6	7.1 ± 1.4	
	M	8.9 ± 7.6	8.8 ± 1.0	10.4 ± 2.7	
	Pooled	7.5 ± 3.5	10.6 ± 4.6	10.3 ± 2.6	9.4 ± 3.8
0.56	Fast				
	F	6.5 ± 3.9	6.7 ± 0.7	12.5 ± 5.6	
	M	6.5 ± 0.2	5.7 ± 1.4	9.0 ± 0.9	
	Slow				
	F	2.9 ± 1.3	4.7 ± 1.4	11.2 ± 0.1	
	M	6.1 ± 1.1	11.0 ± 6.6	18.9 ± 6.2	
	Pooled	5.5 ± 2.3	7.0 ± 3.7	12.9 ± 5.1	8.5 ± 4.9
0.66	Fast				
	F	7.0 ± 0.3	9.7 ± 2.4	10.5 ± 1.2	
	M	4.7 ± 2.1	9.7 ± 0.1	10.5 ± 6.2	
	Slow				
	F	9.6 ± 3.7	8.4 ± 0.2	10.6 ± 1.0	
	M	12.6 ± 13.5	9.0 ± 0.2	9.8 ± 2.8	
	Pooled	8.5 ± 6.2	9.2 ± 1.1	10.4 ± 2.7	9.3 ± 3.9
Pooled		7.1 ± 4.3	8.9 ± 3.6	11.2 ± 3.7	
				Grand average	9.1 ± 4.2

Newtons rounded to nearest tenth. F = female, M = male.

Table 2.8: *Midcycle* pinch force (N) for each experimental condition (mean ± SD).

COF		3.5 N	6.1 N	8.6 N	Pooled
0.33	Fast				
	F	7.2 ± 3.8	12.7 ± 4.1	13.1 ± 3.9	
	M	6.3 ± 0.5	8.5 ± 1.9	11.8 ± 3.5	
	Slow				
	F	9.3 ± 4.4	18.3 ± 13.1	8.1 ± 0.9	
	M	11.0 ± 9.8	9.6 ± 2.4	12.5 ± 4.9	
	Pooled	8.4 ± 4.7	12.3 ± 6.7	11.4 ± 3.4	10.7 ± 5.2
0.56	Fast				
	F	7.4 ± 5.0	7.3 ± 0.9	12.6 ± 5.5	
	M	6.6 ± 0.6	5.4 ± 1.9	9.3 ± 0.9	
	Slow				
	F	3.2 ± 1.7	5.2 ± 2.1	13.3 ± 0.1	
	M	7.0 ± 1.7	12.5 ± 8.2	23.6 ± 9.8	
	Pooled	6.1 ± 2.7	7.6 ± 4.6	14.7 ± 7.1	9.4 ± 6.2
0.66	Fast				
	F	8.4 ± 0.1	9.8 ± 1.5	10.9 ± 1.9	
	M	4.6 ± 2.6	10.0 ± 0.5	11.5 ± 8.5	
	Slow				
	F	12.1 ± 5.4	9.6 ± 1.0	12.4 ± 1.2	
	M	17.2 ± 19.3	10.9 ± 0.1	11.1 ± 3.7	
	Pooled	10.5 ± 9.1	10.1 ± 0.9	11.5 ± 3.7	10.7 ± 5.5
Pooled		7.1 ± 4.3	8.9 ± 3.6	11.2 ± 3.7	
				Grand average	9.1 ± 4.2

Newtons rounded to nearest tenth. F = female, M = male.

Table 2.9: *Peak* pinch force (N) for each experimental condition (mean ± SD).

COF		3.5 N	6.1 N	8.6 N	Pooled
0.33	Fast				
	F	10.3 ± 3.4	16.2 ± 5.7	19.2 ± 2.1	
	M	11.2 ± 0.5	13.3 ± 1.2	18.2 ± 2.0	
	Slow				
	F	12.6 ± 6.6	23.0 ± 14.4	10.8 ± 1.3	
	M	14.3 ± 11.2	14.3 ± 1.5	16.2 ± 2.2	
	Pooled	8.8 ± 3.5	11.3 ± 6.2	20.4 ± 8.0	13.5 ± 7.8
0.56	Fast				
	F	9.5 ± 4.4	10.2 ± 0.6	20.3 ± 8.1	
	M	10.2 ± 0.1	9.6 ± 1.7	13.6 ± 2.2	
	Slow				
	F	4.7 ± 1.7	7.4 ± 0.6	18.2 ± 0.5	
	M	10.9 ± 3.9	18.0 ± 11.8	29.4 ± 10.8	
	Pooled	8.8 ± 3.5	11.3 ± 6.2	20.4 ± 8.0	13.5 ± 7.8
0.66	Fast				
	F	10.3 ± 0.5	15.4 ± 4.0	16.9 ± 1.2	
	M	7.2 ± 2.4	14.6 ± 0.4	15.5 ± 8.0	
	Slow				
	F	15.9 ± 5.0	12.8 ± 1.2	16.3 ± 3.1	
	M	18.7 ± 19.7	13.6 ± 0.6	15.0 ± 5.1	
	Pooled	13.0 ± 9.1	14.1 ± 1.9	15.9 ± 3.9	14.4 ± 5.7
Pooled		11.3 ± 6.4	14.0 ± 5.8	17.5 ± 5.7	
				Grand average	14.3 ± 6.4

Newtons rounded to nearest tenth. F = female, M = male.

pinch force (7.1 N to 11.2 N); a 49% increase in *midcycle* force (8.4 N to 12.5 N); and, a 55% increase in *peak* force (11.3 N to 17.5 N).

Across all experimental conditions, *peak* pinch force was 57% greater than *mean* force (14.3 N vs 9.1 N; $t = 18.6$, $p < .001$) and 39% greater than *midcycle* force (14.3 N vs 10.3 N; $t = 19.3$, $p < .001$). *Midcycle* force was 13% greater than *mean* force (10.3 N vs 9.1 N; $t = 5.9$, $p < .001$).

Individual pinch strengths ranged from 50.7 N to 104.6 N (mean = 73.2, SD = 12.5) for women and from 61.7 N to 149.9 N (mean = 108.6, SD = 17.5) for men. The men were stronger than the women ($t = 9.88$, $p < .001$). Pinch force expressed as a percentage of pinch strength (%MVC) ranged from 2% to 36% depending on the force measure and the experimental condition (Table 2.10).

The most significant predictor for *mean* and *peak* pinch force was the load-strength interaction (Table 2.11); the load effect was greater for stronger individuals (Fig. 2.5). The load-strength interaction explained 17% and 18% of the variability in *peak* and *mean* pinch force, respectively. Adding the main effects, load and strength, to the model explained another 2% of the variation. Load alone explained 15% and 16% of the variation in *peak* and *mean* pinch force, respectively. No other variables were significant. A model

Table 2.10: Percent of maximum voluntary contraction strength (%MVC) used for *mean*, *midcycle*, and *peak* pinch force by load.

	Percent MVC Pinch Force (mean ± SD)		
Load (N)	*Mean*	*Midcycle*	*Peak*
3.5	8 ± 5	9 ± 6	13 ± 7
6.1	10 ± 4	11 ± 5	16 ± 6
8.6	13 ± 5	15 ± 6	21 ± 8

Table 2.11: Predictive models of pinch force (N).

		RMSE	R^2
Mean			
Model I	Fp = 4.26 + 0.79(L)	3.86	0.16*
Model II	Fp = 6.30 + 0.03(S)	4.14	0.03
Model III	Fp = 0.90 + 0.82(L) + 0.04(S)	3.79	0.20*
Model IV	Fp = 5.00 + 0.007(L*S)	3.81	0.18*
Model V	Fp = 0.17 + 0.94(L) +0.04(S) - 0.001(L*S)	3.82	0.20*
Midcycle			
Model I	Fp = 5.33 + 0.81(L)	5.37	0.09*
Model II	Fp = 6.88 + 0.04(S)	5.57	0.02
Model III	Fp = 9.07 + 2.42(P)	5.50	0.05
Model IV	Fp = 4.65 + 0.008(L*S) + 0.03(S*P)	5.13	0.18*
Model V	Fp = 10.05 + 0.01(L) + 0.01(L*S) - 0.08(S) - 8.97(P) + 0.13(S*P)	5.09	0.23*
Peak			
Model I	Fp = 6.95 + 1.21(L)	5.95	0.15*
Model II	Fp = 10.16 + 0.05(S)	6.38	0.03
Model III	Fp = 1.94 + 1.24(L) + 0.05(S)	2.86	0.19*
Model IV	Fp = 8.18 + 0.01(L*S)	5.91	0.17*
Model V	Fp = -0.91 + 1.70(L) + 0.08(S) - 0.005(L*S)	5.90	0.19*

RMSE = Root mean square error; Fp = pinch force in Newtons (N); L = load (N), S = pinch strength (N), P = pace (Fast = 0, Slow = 1).
* Model significant at $p \leq .05$.

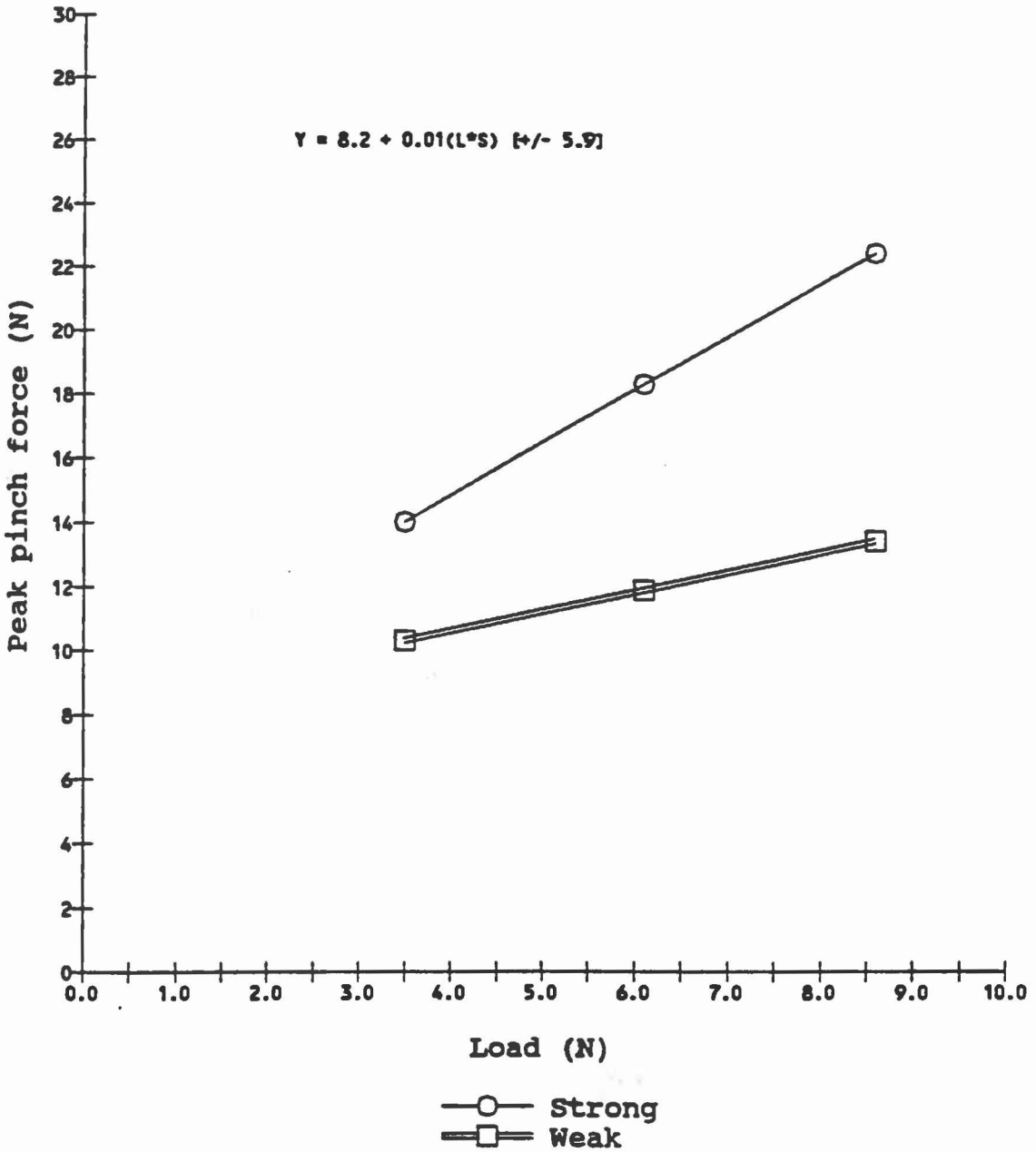

Figure 2.5 Load-strength interaction for peak pinch force. Fp = pinch force (N), L = Load, S = Strength: "weak" = 55 N, "strong" = 150 N.

with all main effects and interactions explained 27% and 28% of the variation in the data for *mean* and *peak* pinch force, respectively.

The most significant predictors for *midcycle* pinch force were the strength-pace interaction and the load-strength interaction. Stronger subjects used more force at the slow pace than at the fast pace, and the load effect was greatest for stronger subjects. A model with the two interactions accounted for 18% of the variability (Model IV, Table 2.11); adding the main effects explained another 5%. Load was the single most powerful variable accounting for 9% of the variability. No other variables were significant. A model with all main and interaction effects explained 24% of the variation.

For pinch force normalized to strength (%MVC), the most significant predictors for *mean* and *peak* force were load and the load-strength interaction (Table 2.12). The load effect was greatest for weaker individuals (Fig. 2.6). Load was the most powerful single predictor, explaining 13% to 19% of the variation in normalized pinch force. The main effects of strength and gender also were significant predictors ($p < .05$). Depending on the force measure, strength explained 11% to 15% of the variation in normalized pinch force; gender explained 11% to 14%.

Table 2.12: Predictive models for %MVC pinch force.

Mean	RMSE	R^2
Y = 4.51 + 2.05(L) - 0.01(L*S)	4.09	0.33
Midcycle		
Y = 7.83 + 1.07(L) - 7.07(G) + 5.79(G*P) -0.85(P)	5.25	0.33
Peak		
Y = 7.27 + 3.27(L) - 0.02(L*S)	6.37	0.34

L = Load (N); S = Strength (N); G = Gender; P = Pace (Fast = 0, Slow = 1); %MVC = Percent maximum voluntary contraction (pinch) strength.

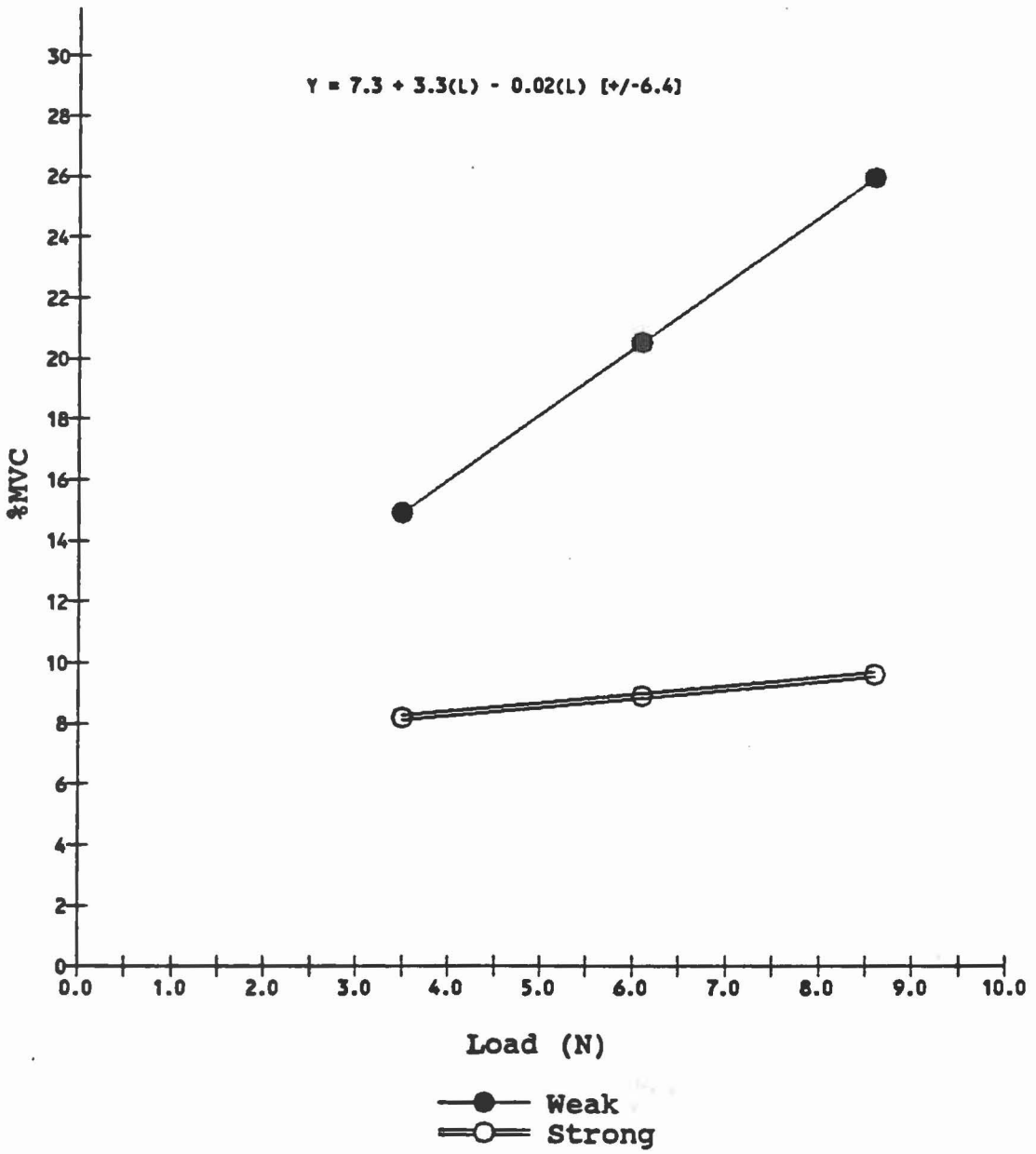

Figure 2.6 Load-strength interaction for normalized *peak* pinch force (%MVC). L = Load, S = Strength: "weak" = 55 N, "strong" = 150 N.

The pinch force to load force ratio (PF:LF), a measure of "overgripping," was related to load force for all dependent variables ($p < 0.01$). The ratio decreased as load increased (Fig. 2.7).

2.5 Discussion

The load-strength interaction was the most significant predictor of all measures of grip and pinch force; the load effect was greatest for stronger subjects, suggesting that stronger subjects "overgrip" by a greater margin than weaker ones (see Fig. 2.5). To lift 15 N, for example, a "strong" subject with a grip strength of 600 N would exert **78** N (*peak*) grip force, whereas a "weak" subject with a grip strength of 200 N would exert **36** N. The interaction may be due to stronger subjects not being as challenged as, and having more reserve than weaker ones. In the Pinch Study, the ratio of pinch force to load force (PF:LF) was significantly related to load, suggesting that overgripping is greater at low loads than at high loads. If this phenomenon exists, stronger subjects would exert more force for a given weight than weaker ones. The practical significance of the load-strength interaction is unclear, however, as it explained only 2% to 7% more of the variation than load alone.

Table 2.12: Predictive models for %MVC pinch force.

Mean	RMSE	R^2
Y = 4.51 + 2.05(L) - 0.01(L*S)	4.09	0.33
Midcycle		
Y = 7.83 + 1.07(L) - 7.07(G) + 5.79(G*P) -0.85(P)	5.25	0.33
Peak		
Y = 7.27 + 3.27(L) - 0.02(L*S)	6.37	0.34

L = Load (N); S = Strength (N); G = Gender; P = Pace (Fast = 0, Slow = 1); %MVC = Percent maximum voluntary contraction (pinch) strength.

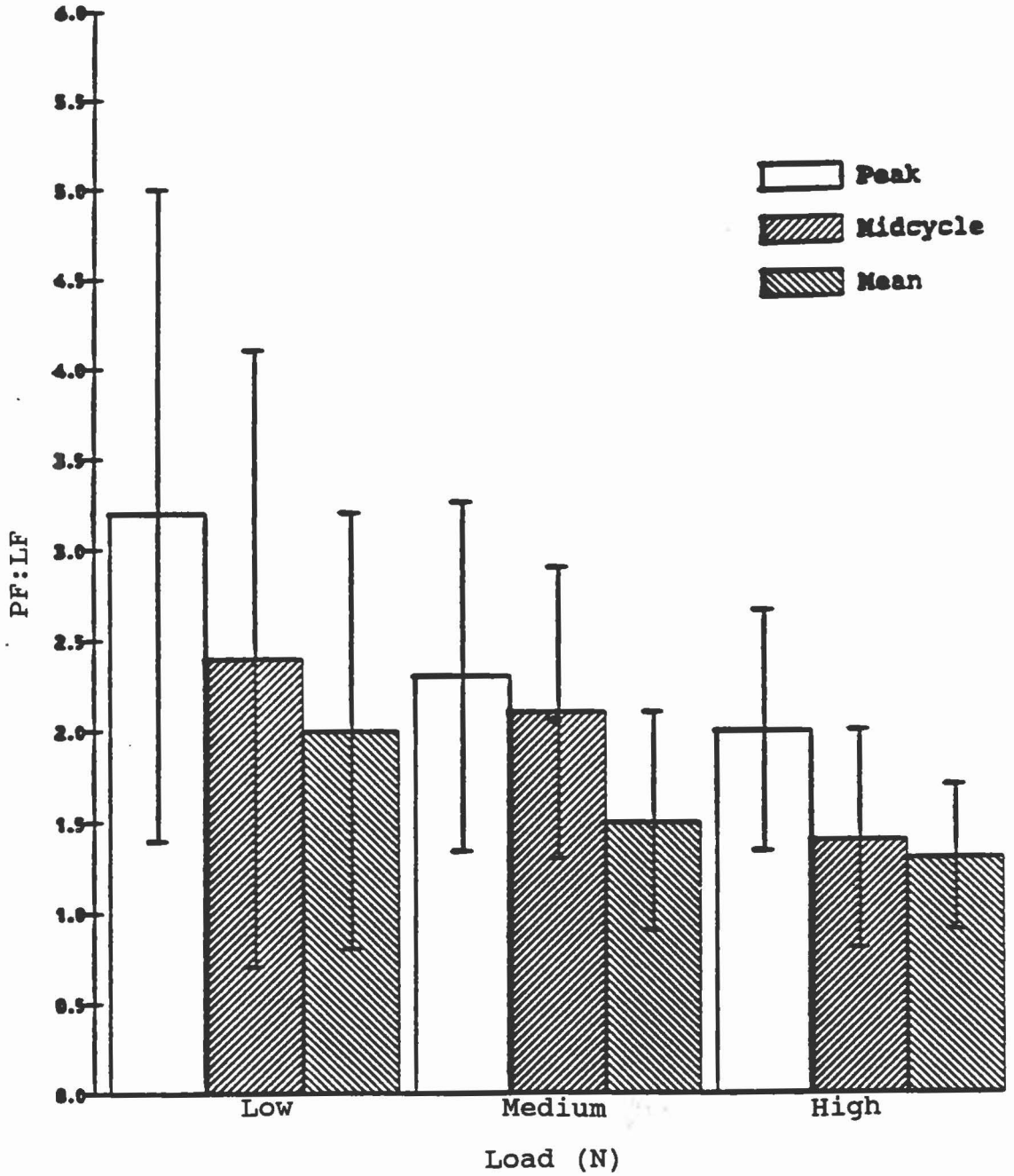

Figure 2.7 Decrease in ratio of pinch force to load force (PF:LF) with increasing load for each force measure.

In the Grip Study, when *mean* and *midcycle* force were normalized to strength (i.e., %MVC), the most important predictors were load and the strength-COF interaction (Table 2.5). Load explained 22% and 26% of the variation for *mean* and *midcycle*, respectively; the strength-COF interaction accounted for another 7% to 8% (Table 2.5). A linear relationship with load is consistent with basic mechanics, and with the results of previous investigations (e.g., Lyman and Groth 1958; Westling and Johansson 1984). A negative COF effect also is consistent with basic mechanics, i.e., grip force is inversely proportional to COF (Armstrong 1985), and with the findings of previous investigations (e.g., Westling and Johansson 1984; Comaish and Bottoms 1971; Johnson 1988). Westling and Johansson (1984) observed that the slope of the linear function between pinch force and object weight for a static holding task was determined by the friction coefficient, i.e., the more slippery the surface, the steeper the slope. Because of the small amount of variation explained, however, the practical significance of a greater COF effect for stronger individuals is limited.

For %MVC *peak* grip force, the most powerful predictors were load, the strength-COF interaction, and the load-pace interaction. Load accounted for 27% of the variation; the strength-COF interaction explained an additional 7%, load-pace, another 4%. The load effect was greatest at the fast

pace which is consistent with basic mechanics (i.e., force is proportional to acceleration).

For %MVC pinch force, the significant predictors for *mean*, *midcycle*, and *peak* force were load and the load-strength interaction (Table 2.12). Not surprisingly, weaker subjects exerted proportionately more force with increasing load than stronger subjects. Load alone explained 13% to 19% of the variation; the load-strength interaction explained 10% to 15%.

In the Pinch Study, models with all main effects and two-way interactions explained 24% - 28% of the variation in the performance data; 17% to 18% of this variation was explained by the load-strength interaction. Load was the single most powerful predictor, explaining 9% to 16% of the variation.

In the Grip Study, full models explained 34% - 42% of the variation in grip force; load alone explained 21% to 25%. The importance of load as a predictor of pinch/grip force is consistent with basic mechanics and with the findings of previous investigators (e.g., Lyman and Groth 1958; Buchholz 1983).

Gender: In both studies, male subjects were significantly stronger than female subjects. Such a finding is consistent with previous research (e.g., Laubach 1976).

Measures of pinch and grip force: For the Pinch Study, *peak* force was significantly (57%) greater than *mean* force and 39% greater than *midcycle* force. For the Grip Study, *peak* force was significantly (65%) greater than *mean* force and 42% greater than *midcycle* force. A similar pattern of *peak* force has been observed by other investigators (e.g., Westling and Johansson 1984; Lyman and Groth 1958). *Peak* force may be attributed to behavioral, physiological, and mechanical factors. Behaviorally, it may represent the individual's attempt to gain control of an object and to search for the slip point. Accordingly, once the object is secure and moving, the individual relaxes the grip force. Physiologically, the subject initially may "overshoot" and, with sensory feedback, modify his or her response. Mechanically, *peak* force may be attributed to inertial effects and the acceleration needed to set an object into motion, and the control needed to change directions repeatedly.

Accordingly, since force is proportional to acceleration, an increase in vertical acceleration will increase the amount of grip/pinch force needed to lift an object. To illustrate, an initial vertical acceleration of

6.87 m/second^2 was measured in a pilot study using a linear accelerometer with a task similar to that of the Grip Study (pace = 60 CPM). Accordingly, if 19.6 N pinch force is needed to support a 2 kg mass at equilibrium (F_{total} = 2 kg * 9.81 m/second^2 = 19.6 N), an additional 13.8 N (2 kg * 6.87 m/second^2) force would be required to accelerate the object (F = 19.6 N + 13.8 N = 33.4 N). Because peak force represents the greatest force exerted in a cycle, it may be the most important factor of fatigue and trauma.

Mean force was significantly lower than *midcycle* and *peak* force. Consequently, *mean* force may underestimate force exerted, particularly if the task is fast-paced.

Of the three force measures, *midcycle* force was the most comparable to the minimal force assumptions of Amonton's Laws of Friction. Accordingly, predictions using a static force analysis were compared to those based on the model for *midcycle* pinch force generated in this study. The force analysis indicated that a 5 N load requires a static pinch force of **7.6 N**, **4.5 N**, or **3.8 N** (mean, **5.3 N**) for aluminum, smooth vinyl, and sandpaper, respectively (COF = 0.33, aluminum; 0.56, vinyl; and 0.66, sandpaper). By contrast, the model for *midcycle* pinch force (Model I, Table 2.11) predicted **9.4 N** pinch force for the combined surfaces (COFs). The value predicted by the empirical model was 77%

higher than the mean value predicted by the static force analysis (i.e., 9.4 N vs 5.3 N). This difference may be attributed, in part, to the type of task: dynamic vs static. The empirical model was based on a dynamic task with presumably greater demands for control than a static task due to inertial effects. A static force analysis assumes that pinch force has stabilized to a minimum level. It has been shown that grip/pinch force tends to peak and then gradually decline, reaching a plateau when the test device is held for prolonged periods (several seconds) (e.g., Westling and Johansson 1984). By contrast, subjects in the present studies did not have time to stabilize their grip/pinch force because the tasks involved short (about one second) holding times.

It is reasonable to assume that rapid movements of an object with frequent changes in direction and, hence, acceleration, and with repeated re-grasping such as occurred in this study, increase the need for control. Increased control, in turn, is achieved by increasing grip/pinch force. Evidence supporting this assumption was found in a study by Westling and Johansson (1984) in which subjects held a test device and moved it horizontally by alternately flexing and extending the wrist through a full range of motion. The authors observed that pinch force increased "considerably" when the wrist's angular velocity exceeded 90 degrees/second.

Inter-subject variability: The coefficient of variation (CV) for the 18 experimental conditions (based on *peak* force) ranged from 7% to 73% (median, 26%) in the Pinch Study, and from 20% to 111% (median, 45%) in the Grip Study. The reason for the greater variability for grip force may be related, in part, to the somewhat higher levels of strength used in the Pinch Study, i.e., 1% to 47% vs 2% to 36% for the Grip Study. Clearly, the wider the interval between the minimum force needed to prevent slipping and the maximum possible exertion (i.e., 100% MVC), the greater the range of possible exerted forces and, hence, variability (Fig. 2.8).

Some of the inter-subject variability may be explained by the amount of "overgripping" found in both studies. For example, if the least amount of force exerted for an experimental condition is defined as the minimal force requirement, exerted force in excess of this can be considered "overgripping." Accordingly, in the Grip Study, subjects exerted from 1.6 to 9.5 times the (*mean*) grip force requirement for a given experimental condition. Overgripping was greatest at the low-load/medium-friction/fast-pace condition. Similarly, in the Pinch Study, subjects used from 1.6 to 7.3 times the minimum force requirement. The greatest difference occurred at the low-load/high-friction/slow-pace condition. Westling and Johansson (1980) reported similar findings, although of a

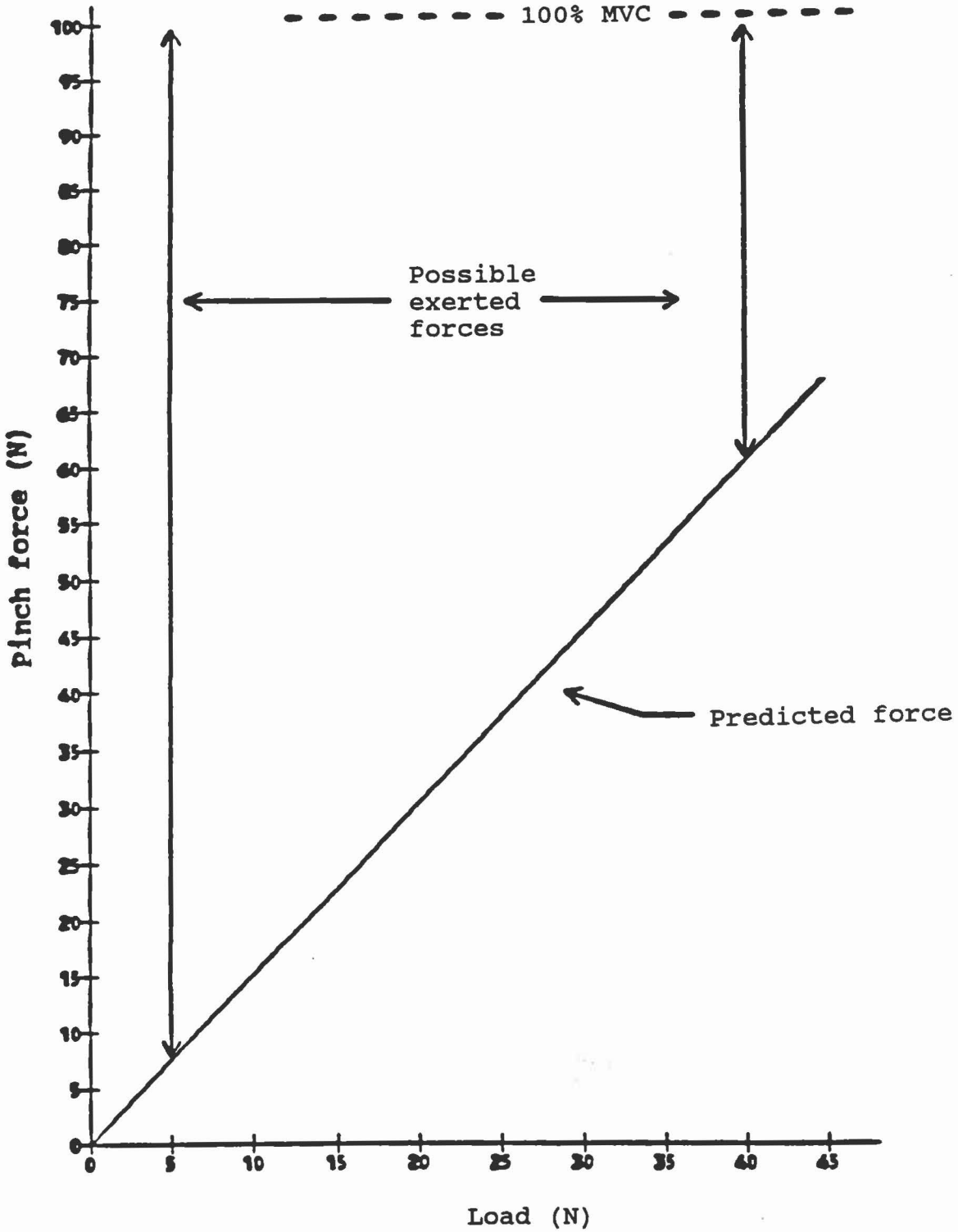

Figure 2.8 Illustration of possible variation in exerted forces using predictions based on a static force analysis (Amonton's Law) for aluminum.

much smaller magnitude. These authors reported that static pinch forces were "about 10-100% above" the minimal force necessary to prevent dropping the test object. They referred to this excess force as a subject's "safety margin" to prevent slipping, and attributed it to differences in tactile sensitivity and attentiveness.

Another likely contributor to inter-subject variability was the pacing procedure. The procedure resulted in some overlap of movement times (i.e., time test object was in transit) between subjects in the slow- and fast-paced groups, particularly in the Pinch Study. The reason for pacing subjects was to measure the effects of work rate, and, hence, acceleration, on exerted forces. In a pilot study for the present research, a significant ($p < .05$) pace effect was found using 15 subjects (9 males, 6 females) and a paired-comparison design in which only pace was varied (Load = 9.2 N; Paces = 60 CPM and 40 CPM; target distance, 45 cm). In the present experiments, however, pace was not a consistent indicator of movement time. Substituting movement time for pace in the stepwise procedure, the most powerful predictor of all measures of pinch force was the load-strength interaction. Movement time accounted for 0.4% to 1% of the variation in pinch and grip force.

In the Grip Study, substitution of movement time produced no changes for *mean* and *midcycle* force, i.e., the

load-strength interaction was the most significant. The most significant predictors for *peak* grip force, however, were the load-strength interaction and the COF-movement time interaction. The slower the movement time, the greater the COF effect. The significance of the COF-strength interaction, which explained 7% of the variation in *peak* grip force, is unclear. Movement time alone explained 0.4% to 0.8% of the variation.

Laboratory simulation: These studies were conducted under controlled laboratory conditions that are different from the work place. For example, the tasks were of short duration, and the socioeconomic consequences of performance were different than they would have been under actual work conditions. Also, the subjects were university students with little, if any, assembly line experience and little training. It has been suggested that, up to a point, the amount of force used in manual work is inversely proportional to the worker's experience (Teisinger 1972; Pyykko *et al.* 1976). No studies investigating this hypothesis could be found, however. If experienced workers consistently use minimal force requirements, their participation in controlled laboratory experiments should reduce inter-subject variability. In future studies, it would be instructive to compare the forces exerted by experienced factory workers and highly-trained subjects to those of inexperienced subjects such as university students.

Laboratory simulation using strain gage devices appears to be a feasible technique for determining the force requirements of some manual tasks. Because of the technical considerations of instrumenting test devices, however, this method is most feasible for the laboratory. Compared to static force analyses, which may underestimate the force requirements of a highly dynamic task (based on results of the present studies), simulation can account for the dynamic aspects of tasks. Compared to EMG, interpretation of the response variable (output signal) is straight-forward. This, in itself, should result in lower inter-subject variability. Even under controlled laboratory conditions, however, it may not be possible to account for all sources of variability in the data. In the present studies, less than half (i.e., 24% to 42%) of the variability could be explained using a model with all main effects and two-way interactions. Within limits, the amount of force applied, vs minimum required, is voluntary. Part of the unexplained variability, therefore, may be related to behavioral characteristics of subjects (e.g., attentiveness and level of anxiety).

Results of these experiments suggest that for highly dynamic tasks in which inertial effects are a consideration (with loads less than 20 N), individuals may exert considerably more force than expected based on a static

force analysis. In future studies, it would be instructive to increase holding times by using longer cycle times, thus permitting an assumption more consistent with that underlying Amonton's Laws, i.e., of using the minimal force to prevent slipping.

2.6 Summary and Recommendations

1) Load was the most potent predictor of pinch and grip force; it explained 9% to 25% of the variation in the performance data.

2) The load-strength interaction was the most *statistically* significant predictor of all grip and pinch force measures; it explained 17% to 32% of the variation in performance data. The practical significance of this interaction is limited, however, as it explained only 2% to 7% more variation than load alone.

3) For normalized grip force (i.e., %MVC), the most statistically significant predictors of %MVC *mean* and *midcycle* grip force were load and the strength-COF interaction. The negative COF effect, i.e., less force required for higher frictional surfaces, is consistent with basic mechanics. The practical significance of the interaction with strength (i.e., a greater effect for

stronger subjects), however, is unclear. The interaction explained 7% and 8% of the variation in pinch and grip force compared to load which explained 22% and 26%. For normalized *peak* grip force, in addition to load and the strength-COF interaction, a load-pace interaction was present. The load effect was greatest at the fast pace. Although such an interaction is consistent with basic mechanics, its practical significance is limited because it explained only 4% of the variation.

4) For normalized *mean* and *peak* pinch force, the most significant predictors were load and the load-strength interaction. The load effect was greatest for weaker subjects, i.e., they used proportionately more force with increasing load than did stronger subjects.

5) The lack of a significant COF main effect on pinch or grip force may be related to the relatively low loads and narrow range of frictional surfaces used which made it difficult to see subtle effects. To determine when a COF effect becomes significant, future studies of pinch and grip force should consider using a wider range of COFs, and loads that require a higher percentage of strength than used in this study (i.e., greater than 50% MVC).

6) Pace was not a significant predictor of pinch and grip force and was not a consistent indicator of movement

time and, hence, acceleration. Some overlap in movement times between subjects in the fast- and slow-paced groups was observed. Future studies involving subject pacing should consider designs which minimize inter-subject variability in and overlap of movement times, e.g., designs that repeat on pace. Also, training time could be increased and subjects' performance controlled through instructions and biofeedback. It should be recognized, however, that some variation is inevitable, and that interventions that minimize variability may themselves become confounding factors. Possibilities are 1) to use a wider interval between paces than used in this study, and 2) to use an incentive system in which one group works as "fast as they can" and another group works at a "comfortable" pace (i.e., using movement time as a covariate).

7) In both studies, evidence of "overgripping" was observed. In the Grip Study, subjects exerted from 1.6 - 9.5 times the theoretically minimal (*mean*) grip force; in the Pinch Study, subjects used from 1.6 - 7.3 times this amount. In the Pinch Study, the ratio of pinch force to load force (PF:LF) decreased as load force increased indicating a greater tendency to overgrip at low loads. These results have implications for intervention techniques to prevent CTDs such as training workers to use minimal force to perform a "light" task, and using biofeedback techniques to warn of overgripping.

8) Full models, with all main effects and two-way interactions, explained from 24% to 42% of the variability in performance data depending on the force measure. The majority of variability in hand force data, therefore, remains to be explained. Factors that may account for this variability are motivation (assessed by mood and personality measures), experience, and task length.

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CHAPTER 3

AN INVESTIGATION OF PINCH FORCE, FRICTION AND WEIGHT

3.1 Abstract

A laboratory study using a 2 X 3 complete repeated measures design and 10 male subjects was conducted to evaluate the effect of COF on pinch force at loads requiring 50% or more of maximum voluntary contraction (MVC). Sandpaper (320 grit) and smooth aluminum were tested with three loads: 7.5 N, 24.5 N and 41.5 N. On average, the high load represented 48% (± 18%) MVC for sandpaper and 70% (± 12%) MVC for aluminum. The dependent variables were peak and static pinch force. The task was a simple "Pick & Place" involving slow, self-paced movements. Overall, the main and interaction effects of load and COF for both dependent variables were significant at the 1% level. However, analysis by load showed that the COF effect was statistically significant ($p < .01$) only at the high load. These results suggest that, under conditions similar to those of this study, high-friction handles will have the most conspicuous effect at high load forces.

This has implications for tool design and for worker training, e.g., instruction and feedback to minimize exerted forces.

3.2 Introduction

Forceful exertion of the hands and arms is a risk factor for cumulative trauma disorders (CTDs) of the upper extremities such as tendinitis and carpal tunnel syndrome (e.g., Thompson, Plewes and Shaw 1951; Smith, Sonstegard and Anderson 1977; Falck and Aarnio 1983). Most data collected on the relationship between force and CTDs has been qualitative and, consequently, has not supported development of a quantitative definition of excessive force for specific tasks. One reason for the lack of such data is the difficulty of measuring hand force exertion in manual work. Measurement of the dose - response relationships between force and CTDs is a prerequisite, however, if quantitative guidelines are to established. The study described in this report is one of two in which the effect of selected task factors on the amount of hand force exerted to perform manual tasks was examined (Ch. 2). The goal of this research was to contribute towards the development of a methodology by which the force requirements of manual tasks can be determined.

Previous studies in this series examined the effect of load, work pace, coefficient of friction (COF), gender and grip/pinch strength on the amount of grip/pinch force used to perform a simple, repetitive task (Ch. 2). COF did not have a significant effect on pinch or grip force except when normalized to strength, and, then, only for grip force. The reason for the latter finding is unclear. A COF effect had been expected based on the laws of static friction and on the findings of previous investigators (Armstrong 1985; Westling and Johansson 1984; Johnson 1988), as well as by common experience, e.g., the difficulty of picking up slippery objects. This topic is discussed in detail in Chapter 2.

The lack of COF effect in previous studies (Ch. 2) was attributed primarily to large inter - subject variability. The variability was attributed, in part, to the low loads used in the tasks, i.e., loads that required subjects to use a low percentage of their maximum voluntary contraction strength (%MVC). For example, average pinch force levels were in the 6% to 21% MVC range, depending on the experimental condition and the force measure. The basis for the above conclusion was that the range of possible exerted forces was wider at lower %MVC levels, and, therefore, the potential for variability was greater. The purpose of the present study was to determine the effect of COF on pinch force at loads in the 50% to 100% MVC pinch force range.

3.3 Methods

3.3.1 *Subjects*

Ten healthy male university students (18-29 years old) were recruited and paid for their participation. The reason for using one gender with a narrow age range was to provide homogeneity in terms of grip strength and work experience. Maximum voluntary contraction pinch strength (MVC) ranged from 78.6 N to 127.9 N (mean = 102.0, SD = 20.6). Criteria for acceptance was a negative history of paraesthesias (e.g., numbness or tingling) or any trauma or surgery which might impair tactile sensitivity or ability to perform the task. Subjects were given a brief verbal description of the task and a questionnaire to determine their eligibility and to elicit demographic data such as age and work history. Informed consent was obtained. The study was conducted in a laboratory on the campus of a local university.

3.3.2 *Experimental design and data analysis*

The study was a complete repeated-measures design (Winer 1971) that investigated the effect of COF on applied pinch force at three levels of load. A computer-based pseudo-random number generator determined the order of the six treatment conditions. A cycle was defined as movement to a target. Two cycles (one trial) were performed for each treatment condition. Repeated measures analysis of variance

(ANOVA) was used to determine the main effects of load and surface (COF) and their interaction on the amount of pinch force used to perform the task. ANOVA for repeated measures also was used to evaluate the effect of load and COF on the ratio of pinch force to load force (PF:LF) and pinch force normalized to maximum voluntary contraction strength or %MVC. A paired t-test with a Bonferroni adjustment was used to evaluate the difference between peak and static force for each experimental condition and between surfaces for each load (Neter and Wasserman 1974).

To maximize any possible COF effects, two materials from our previous study were selected that had the greatest difference in hand/material COF, i.e., 320 grit sandpaper (COF = 0.66 ± 0.11) and smooth aluminum (COF = 0.33 ± 0.09) (cf. Buchholz, Frederick and Armstrong 1988). The loads were 7.5, 24.5 and 41.5 N. The heaviest load was selected by a pilot study (n = 6 males) to determine the maximum load the weakest subject could lift and move horizontally using the more slippery surface, i.e., aluminum. This produced an initial estimate of about 45 N. To prevent undue fatigue during the study which involved repeated movements, the upper limit was lowered to 41.5 N. For comparison purposes, the lowest level was chosen to overlap loads used in our previous study of pinch force (Ch. 2), i.e., 3.5 to 8.6 N; the middle level was midway between the upper and lower loads.

The motion was an MTM (Methods-Time Measurement) "C" Move, i.e., the object was moved (45 cm) to an exact location (Smith 1978).

3.3.3 *Apparatus*

An adjustable table was the simulated work station (Fig. 3.1). Pinch force was measured with a strain-gage dynamometer (Pronk and Niesing 1981) built into a custom-designed test device that could accommodate a range of loads and different surface coverings (Fig. 3.1). Strain gage signals were amplified and collected at 20 Hz with a micro-computer using a 12-bit analog-to-digital converter and commercial data acquisition software.

3.3.4 *Procedure*

Before starting the task, the height of the workstation was adjusted to 17.5 cm below the tip of the subject's third finger with the fingers outstretched and the forearm parallel to the side (Fig. 3.1). This posture was chosen to minimize load moments on the wrist and elbow so that the fingers were the strength-limiting joint. Subjects used their dominant hand to move the test object between two targets releasing it each time. Subjects were instructed to move the object "slowly and smoothly" over a period of several seconds. At least one practice cycle was allowed

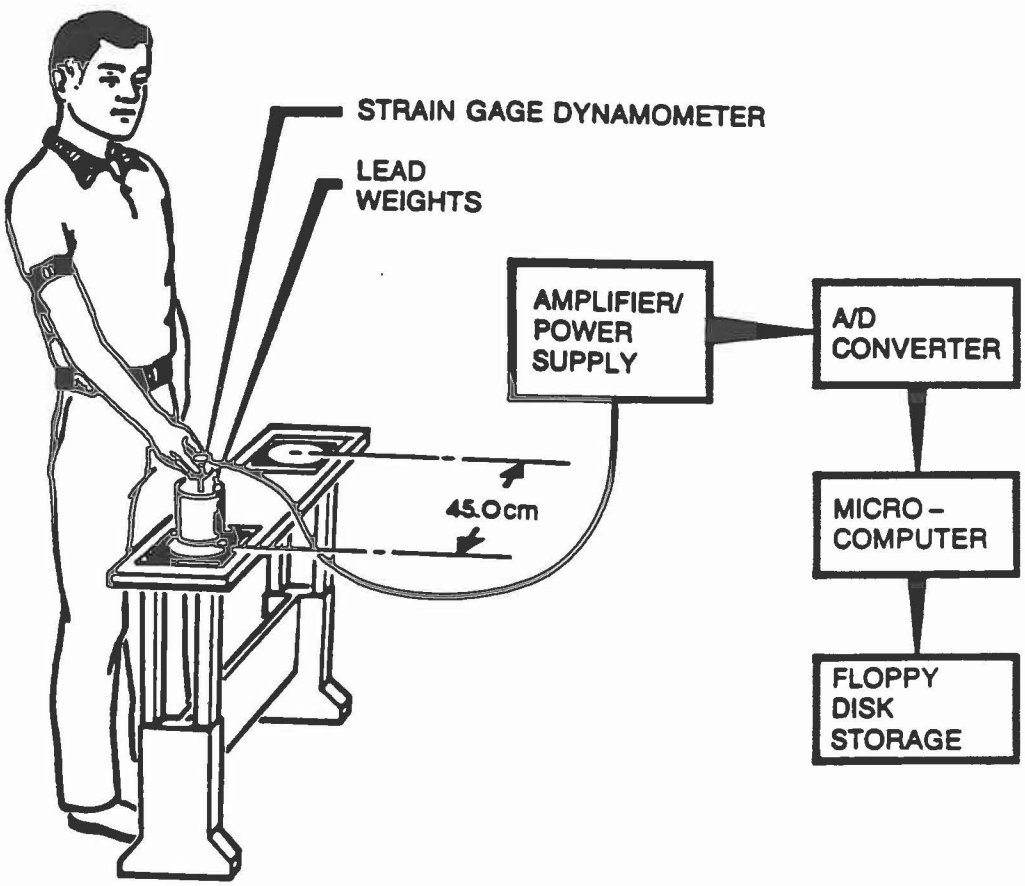

Figure 3.1 Experimental apparatus and setup.

for each experimental condition. Each cycle was followed by a 45 - second rest period.

Pinch strength was measured at the end of the session after a two - minute rest period, using the same hand and body posture and the same test device, weights removed. Two maximal exertions were performed, each followed by a 45 - second rest period. The measurement criterion was the average peak force for the two exertions.

3.4 Results

Most cycles followed a typical pattern. Pinch force peaked initially and fell quickly to a roughly stable plateau before dropping to zero as the device was placed on a target and released (Fig. 3.2). The two measurement variables were the peak (the maximum force exerted) and the static pinch force in each cycle, averaged over two cycles. Static force was defined as the force exertion one second before release of the device (Fig. 3.2). The latter measurement was chosen to correspond with the pinch force exertion during the plateau described above. For each experimental condition, peak force was significantly greater than static force ($p < .01$.). The average difference between peak and static force for the six experimental conditions was 54% (range from 28% to 65%).

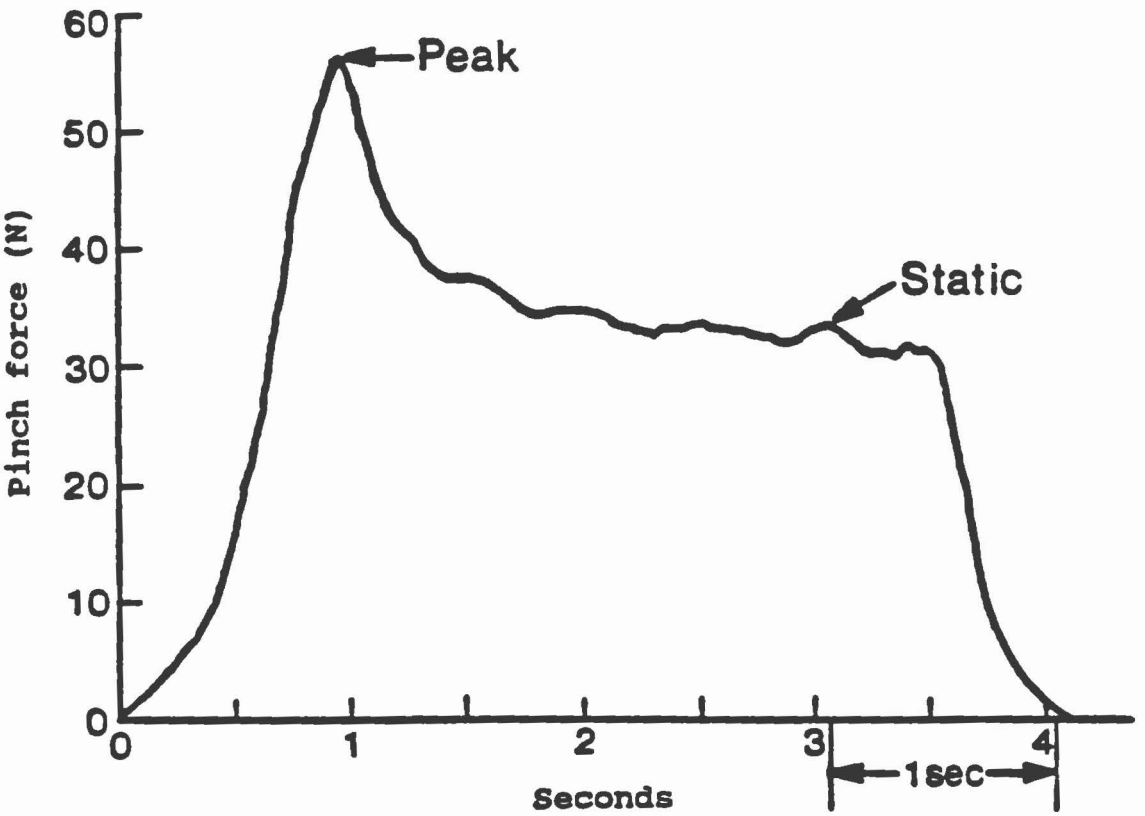

Figure 3.2 Pinch force data from a typical cycle.

For static pinch force, a **five**-fold increase in load (7.5 N to 41.5 N) resulted in a **three**-fold increase in pinch force (9.6 N to 31.1 N) for sandpaper and a **five**-fold increase in pinch force (9.8 N to 54.1 N) for aluminum (Table 3.1). For peak force, the **five**-fold increase in load resulted in a **three**-fold increase in pinch force for sandpaper (15.8 N to 46.3 N), and a **four**-fold increase in pinch force for aluminum (16.4 N to 69.5 N).

For peak pinch force, the main effects of both load and COF were significant ($F[2,18] = 136.29$, $p < 0.01$ and $F[1,9] = 14.53$, $p \leq 0.01$, respectively). The interaction between load and surface also was significant ($F[2,18] = 8.02$, $p < 0.02$) (Fig. 3.3). The difference in pinch force between sandpaper and aluminum was significant only at the high load (paired t-test with Bonferroni adjustment, $t = -5.10$, $p \leq .01$).

For static pinch force, the main effects of load and COF were statistically significant ($F[2,18] = 129.47$, $p < .001$, and $F[1,9] = 30.28$, $p < .001$, respectively). The load - COF interaction also was significant ($F[2,18] = 20.09$, $p < .001$) (Fig. 3.4). The difference in pinch force between sandpaper and aluminum was significant only at the high load ($t = -9.69$, $p < .001$).

Table 3.1: Static and peak pinch force (mean ± SD) for the six experimental conditions (n = 10).

	Load (N)		
	7.5	24.5	41.5
Surface			
Sandpaper			
Static	9.6 ± 7.5	22.7 ± 9.2	31.1 ± 6.4*
Peak	15.8 ± 11.2	36.2 ± 14.2	46.3 ± 10.9*
Aluminum			
Static	9.8 ± 4.4	31.7 ± 5.9	54.1 ± 8.0*
Peak	16.4 ± 5.6	48.8 ± 7.5	69.5 ± 6.8*

* Significant difference $p < .01$) between aluminum and sandpaper.

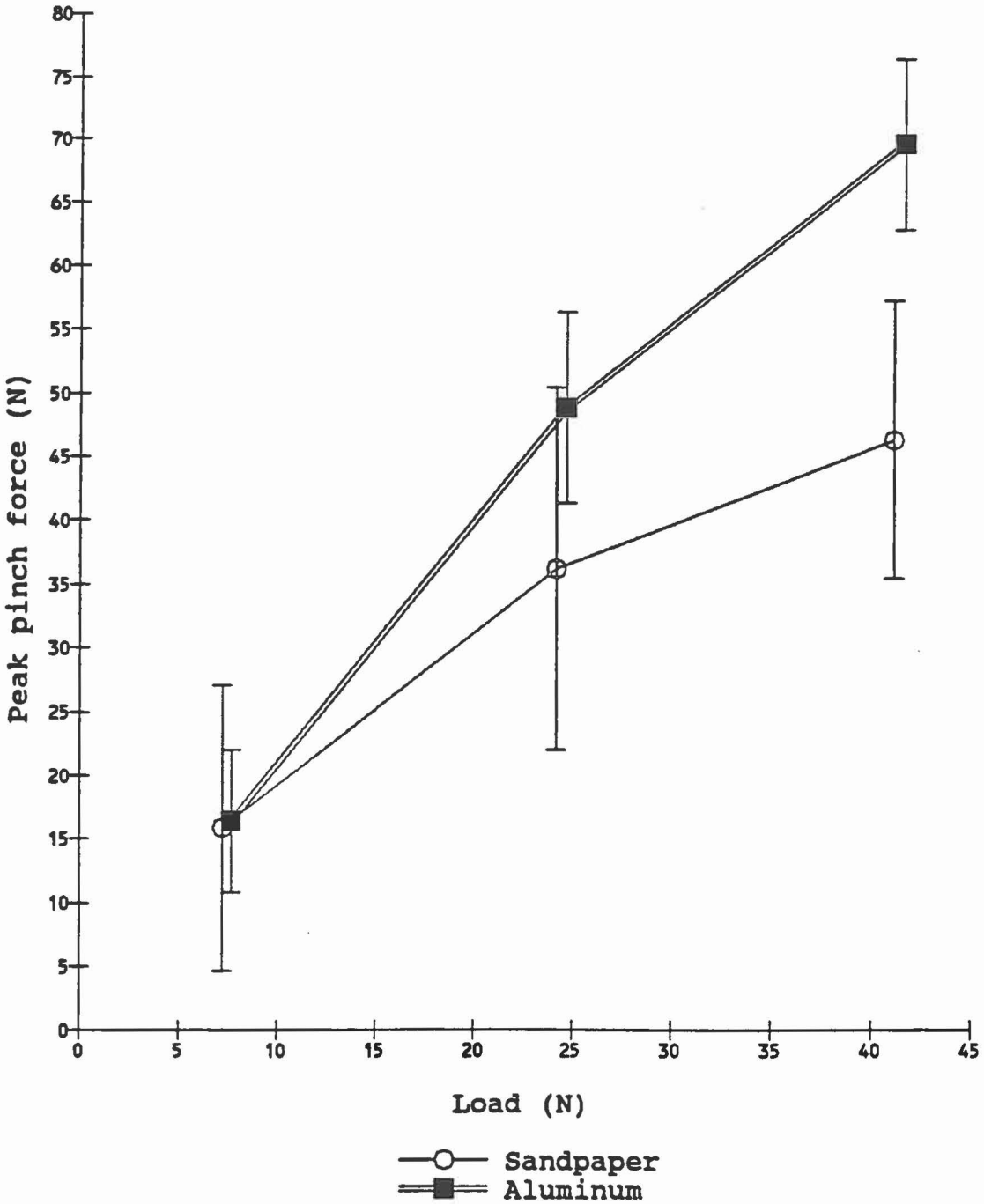

Figure 3.3 Interaction of load and COF for peak force.

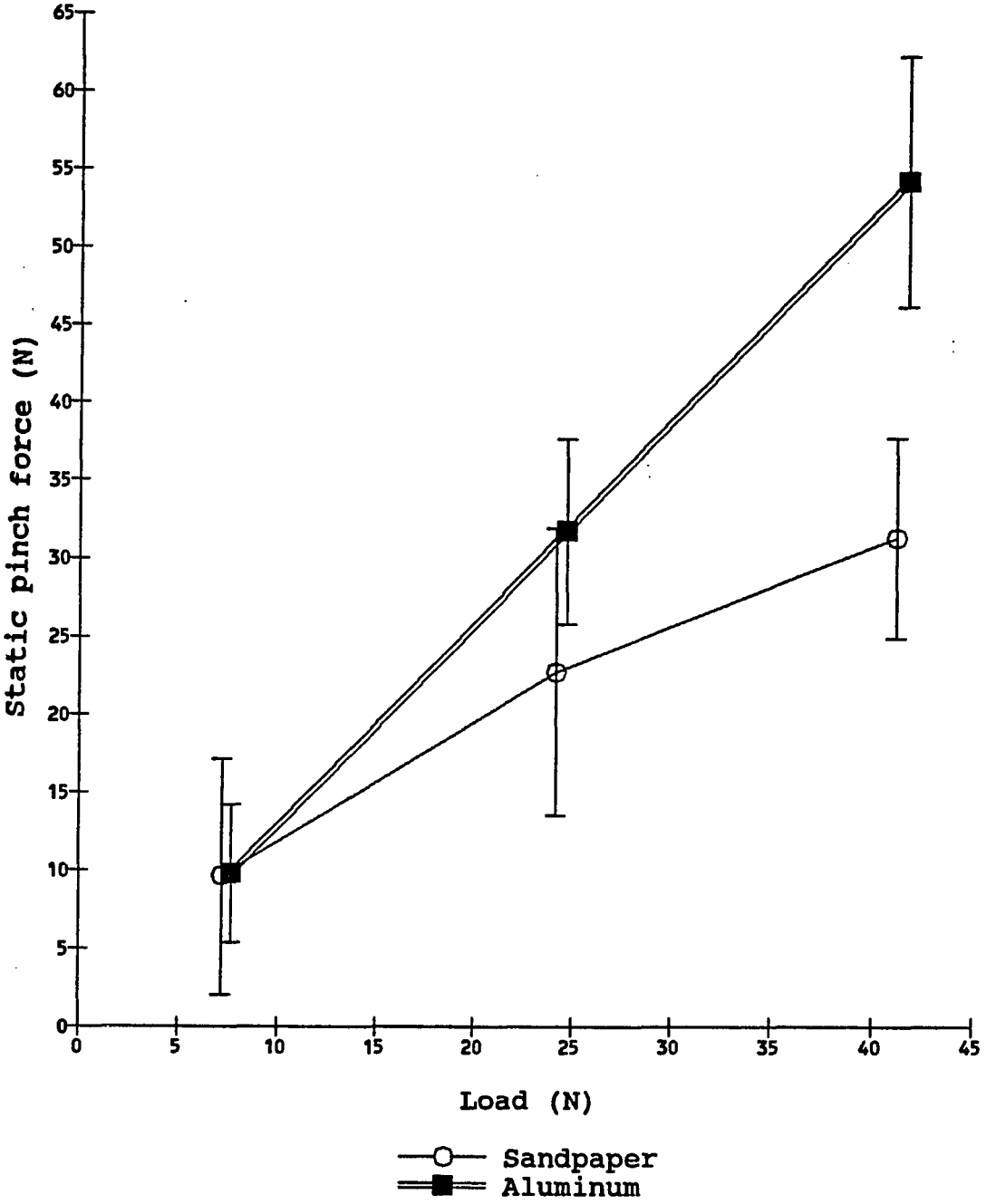

Figure 3.4 Interaction of load and COF for static force.

For peak and static pinch force normalized to strength, i.e., %MVC, the main and interaction effects of COF and load were significant at the 1% level. The percent of strength used for the six experimental conditions (averaged over 10 subjects) ranged from 17% to 70% for peak force and from 10% to 55% for static force (Table 3.2). To perform the task under the most challenging experimental condition, i.e., high load, aluminum surface, subjects used from 50% to 84% of MVC (individual values).

For pinch force expressed as a ratio of load force (i.e., PF:LF), COF had a significant effect ($p < .02$) on static force; the ratio was higher for aluminum. COF did not have a significant effect on peak force. Load did not have a significant effect on either peak or static force ($p > .05$).

Predicted pinch force, based on a static force analysis using Amonton's Law (Armstrong 1985), was compared to average static force exertions for each experimental condition using published values for COF (cf. Buchholz *et al.* 1988). All but two of the six observed forces (averaged over 10 subjects) were within 1 SD of the predicted mean (Table 3.3 and Fig. 3.5).

Table 3.2: Percent MVC for each experimental condition (averaged over 10 subjects).

	7.5 N	24.5 N	41.5 N
Sandpaper			
Peak	17 ± 14	37 ± 15	48 ± 18
Static	10 ± 9	23 ± 9	32 ± 9
Aluminum			
Peak	17 ± 8	50 ± 13	70 ± 12
Static	10 ± 5	32 ± 10	55 ± 12

Table 3.3: Comparison of predicted and observed values of *midcycle* pinch force (mean ± SD) for each load and surface (COF) condition.

	Pinch Force (N)	
	Predicted	Observed
Aluminum		
7.5 N	12.3 ± 3.3	9.8 ± 4.4
24.5 N	40.1 ± 10.9	31.7 ± 5.9
41.5 N	68.0 ± 18.6	54.1 ± 8.0
Sandpaper		
7.5 N	5.9 ± 1.0	9.6 ± 7.5*
24.5 N	19.1 ± 3.2	22.7 ± 9.2*
41.5 N	32.3 ± 5.4	31.1 ± 6.4

Observed pinch force averaged over 10 subjects.
COF = 0.33 ± 0.09, aluminum; 0.66 ± 0.11, sandpaper.
*Greater than 1 SD of the mean.

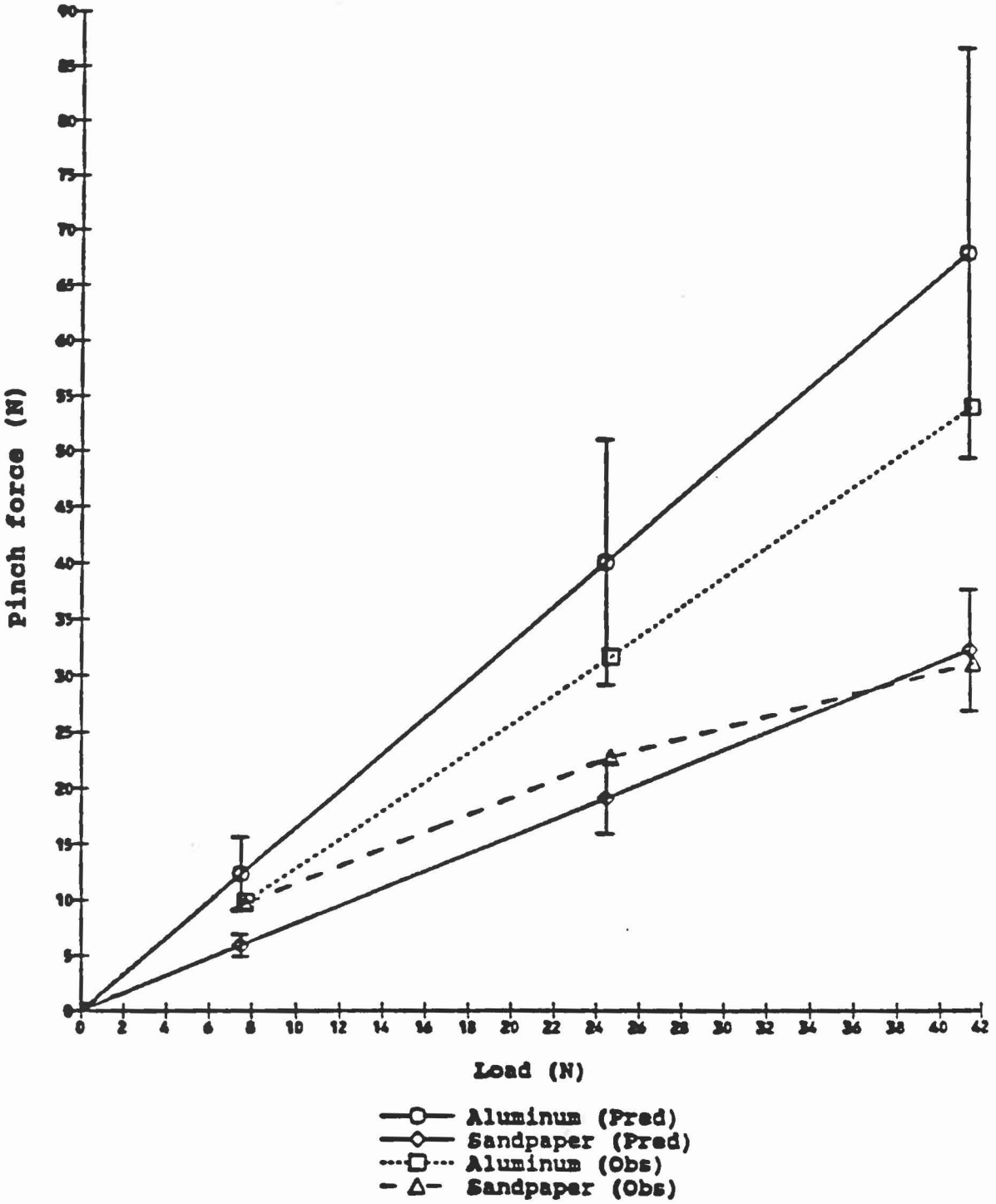

Figure 3.5 Predicted vs observed forces.

3.5 Discussion

The effect of COF on both static and peak pinch force varied with the load, and was statistically significant only at the high load (see Table 3.1, Figs. 3.3 and 3.4). At the high load (41.5 N), peak pinch force exertions (group averages) represented 48% of MVC for sandpaper and 70% of MVC for aluminum. Individual values were as high as 84% MVC. For the low and medium loads, at which average %MVC levels (for peak force) were between 10% and 50%, no statistical difference in applied force was detected between aluminum and sandpaper. A likely explanation is that the maximum theoretical difference between the pinch force required to pick up the test object for sandpaper and that for aluminum at the low and medium loads was smaller than the inter-subject variability in exerted forces. Support for this conclusion is provided by the over three-fold difference in coefficient of variation (CV) between the low and high loads (sandpaper) for static pinch force, i.e., 78% vs 21% (Table 1). As discussed in the previous study of pinch force (Ch. 2), the lower the load, the more potential variability in applied pinch force due to the wide range between the minimum required and the maximum possible force.

In a series of related studies, Westling and Johansson (1980, 1984) (Johansson and Westling 1985) evaluated the effect of COF and load on the amount of pinch force employed

for a static manual task. Although results were not tested for statistical differences, the authors reported a load and a COF effect using sandpaper, suede, and silk, and loads from 2.0 N to 8.0 N. Specifically, the slope of the linear function between load and pinch force was determined by the friction coefficient. Westling and Johansson (1984) concluded that pinch force was "critically balanced" to prevent slipping and excessive overgripping. By comparison, in the present study, no COF effect was found at a similar load (7.5 N). The reason for the difference in findings can be explained in part by the type of tasks, i.e., a static, precision motor activity for the former vs a dynamic, gross motor activity for the present study. The argument is that when individuals are doing several tasks at once, as in the dynamic task (i.e., lifting the object, changing directions, accelerating, and re-grasping each time the direction is changed), they employ additional force to insure control. Westling and Johansson (1984), for example, found that when their subjects incidentally performed two simultaneous motor activities, e.g., scratching an itch while performing the experimental task, applied pinch force increased.

Another possible reason for the difference in findings between Westling and Johansson (1984) and those of the present study is the narrower range of frictional surfaces used in the latter. The highest frictional surface used by Westling and Johansson (sandpaper) was 3.5 times greater

than their most slippery surface (silk). By comparison, in the present study, the highest COF (sandpaper) was two times greater than the lowest COF (aluminum). It is reasonable to assume that the wider the interval between levels of a factor, the more likely it is that an effect will be detected, especially if it is subtle.

Force analyses: A force analysis based on Amonton's Law adequately predicted pinch force exertions for the static phase of the task cycle. For the six experimental conditions, all but two observed values were within 1 SD of the predicted mean value, and these were only 1% and 3% higher (Table 3.3). By contrast, in our previous study of pinch force, predicted values based on the model developed for *mid-cycle* force, the roughly static phase of the force cycle, were 77% higher than predictions based on Amonton's Law (Ch. 2). The reason for the difference in findings between the two studies likely is due to the amount of time the object was held, specifically, the length of the static phase of the force cycle. Movement times in the previous study were rapid enough that the static phase likely was too short (roughly 1 second) to allow pinch force to stabilize at a minimum level. Thus, a basic assumption for using Amonton's Laws, i.e., of minimal force conditions, was not met (Armstrong 1985). Using a static, holding task, Westling and Johansson (1984) found that pinch force decayed to an approximately stable plateau after about one second

when total holding times were 10 to 15 seconds. In the present study, the object typically was held for several seconds, therefore, pinch force had more time to stabilize to a minimal plateau.

Some of the observed pinch forces were lower than predicted values, i.e., for aluminum and for sandpaper, high load (Fig. 3.5). It is probable that the coefficients of friction actually were somewhat higher than those found by Buchholz *et al.* (1988) because of the type of hand preparation. In the latter study, subjects' prepared their hands by washing them with soap and water, and drying with a paper towel. In the present study, this method of preparation was infeasible. Subjects washed their hands with a commercial, moist towellette and let them air dry. A pilot study comparing the two types of hand preparation (n=2) found that subjects used roughly 10% less pinch force when their hands had been prepared with a towellette than with soap and water. Accordingly, higher COFs (i.e., than those of Buchholz *et al.* 1988) would result in lower predicted forces than those shown in Figure 3.5 and Table 3.3.

In our previous study of pinch force (Ch. 2), subjects tended to overgrip at low loads, i.e., the ratio of pinch force to load force (PF:LF) decreased as load increased. Although a similar pattern was found in the present study

for peak pinch force, the relationship was not statistically significant. It is reasonable to expect that overgripping would be less apparent at heavier loads because the task is more challenging and subjects have less reserve.

3.6 Summary and Recommendations

Friction affects pinch force exertions at near maximal weights, i.e., loads those requiring roughly 50% or more MVC. This conclusion is most applicable to conditions similar to those of this study, e.g., with metal and vinyl-covered handles, and for dynamic, slow-moving tasks.

Amonton's Law provides a reasonable estimate of forces exerted at high load forces for slow-moving, dynamic tasks involving a frictional hand/handle coupling.

In future studies of pinch and grip force, it would be instructive to use more loads and a wider range of friction coefficients than used in this study to determine more precisely when COF becomes important.

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CHAPTER 4

A SYSTEM FOR DESCRIBING AND CLASSIFYING THE FORCEFUL ELEMENTS OF MANUAL WORK

4.1 Abstract

A taxonomy was developed for describing and classifying forceful elements of manual work. The taxonomy is based on traditional work-methods analysis concepts. Five major work objectives are identified. The first four objectives concern direct use of the hand(s): MOVE, HOLD, DEFORM, and APPLY TORQUE. The fifth objective, USE TOOL, has nine categories that describe various generic tool actions: secure threaded fastener, secure non-threaded fastener, cut, strike, grind/polish, stretch/compress, stir/spread, drill, and move/hold. Force attributes, variables that affect the force requirements for each objective, are identified.

The taxonomy could be used for job analyses to help identify and control ergonomic stresses. Also, the taxonomy provides a common terminology and framework for the development of a standardized system for determining the force requirements of manual work.

4.2 Introduction

Forceful exertion is a risk factor for cumulative trauma disorders (CTDs) (e.g., Thompson, Plewes, and Shaw 1951; Falck and Aarnio 1983; Armstrong, *et al.* 1987). Armstrong and colleagues (1987) for example, found that the risk of hand-wrist tendinitis was 29 times greater for workers performing high force-high repetition jobs than for those performing low force-low repetition jobs. Because force in manual work is difficult to measure, it is seldom defined or measured. Consequently, available guidelines for reducing manual force have been qualitative (e.g., Armstrong *et al.* 1986; Tichauer 1966). To establish quantitative guidelines for work design, and to gain an understanding of the dose-response relationship between hand force exertion and CTDs, it is important to determine the force requirements of manual tasks. This paper focuses on the development of a system for describing and classifying the forceful elements of manual work. This taxonomy could serve as the foundation for a database for needed quantitative data, and for the development of system for determining the force requirements of manual tasks.

Previous work: Most data regarding the force requirements of manual tasks have been qualitative using terminology such as "heavy" and "forceful" (e.g., Thompson, Plewes and Shaw 1951; Falck and Aarnio 1983; Tanzer 1959).

Little quantitative data exist, and what data exist have not been compiled or organized into a format for determining the force requirements of manual tasks. One of the likely reasons for this not having been done is the complex nature of and difficulty in measuring manual force.

Sporadic attempts have been made to estimate hand force exertions using mechanical models (Armstrong 1985), electromyography (EMG) (e.g., Radwin, VanBerjeijk and Armstrong 1989; Silverstein, Fine and Armstrong 1986, 1987), strain gages (e.g., Radwin, Armstrong and Chaffin 1987; Lyman and Groth 1958; Keller, Taylor and Kahm 1947) and psychophysics (i.e., force-matching) (Yonda 1985). Keller et al. (1947) determined the hand force requirements of selected activities of daily living such as eating and dressing. The purpose of this study was to establish guidelines for the design of hand prostheses. Although the authors reported force levels for specific tasks, the results of this study were difficult to evaluate based on the limited description of their procedures and because only one subject was used.

The focus of recent investigations of manual force has been on measuring the effect of selected factors such as load, vibration, handle shape, tool torque, and surface frictional conditions on manual exertions (e.g., Farkkila, Pyykko, Korhonen and Starck 1979; Westling and Johansson

1984; Johnson 1988; Radwin et al. 1987; 1989; Lyman and Groth 1958; Ch. 2). These studies examined whether statistically different force magnitudes were exerted under the various experimental conditions. Lyman and Groth (1958), for example, measured the effect of load, distance moved, direction of move and protective hand covering on applied pinch forces. All main effects, except direction moved, were statistically significant, with load being the most important. Johnson (1988) reported that subjects used significantly (16%) less grip force to operate a powered screwdriver when a high-friction (vinyl-covered) handle was placed over a standard a low-friction (aluminum) handle.

In a previous study (Ch. 2), the amount of variation in pinch and grip force that could be explained by selected task and personal factors was investigated. Other investigators have characterized force categorically, e.g., as high or low. Silverstein et al. (1986), for example, measured the association between exposure to repetition and force and the development of CTDs. Average hand forces greater than 4 kg (estimated with EMG) were considered high; forces less than 1 kg were low. Some low-force jobs were classified strictly on the basis of inspection and knowledge of the job. Force exertions for specific tasks or elements of tasks were not reported.

The complexity of determining manual force exertions and the general lack of quantitative manual force data suggest the need for a standardized method for estimating hand force. Such a method would be easy to use, reliable, and require a minimum amount of equipment. It would be based on observable or measurable properties of manual activities and would have a clearly defined terminology. It would allow for rapid determination of the force requirements of manual tasks in most industrial settings. As such it would be analogous to the **Predetermined Time Systems (PTS)** used by industrial engineers to establish the normal time required to perform a task such as Methods - Time Measurement (MTM) and Basic Motion Time Study (BMT) (Smith 1978). The purpose of this paper is not to develop a complete system but to provide a foundation for it. It is proposed that before such a system can be developed, a taxonomy for describing and classifying the forceful aspects of manual work is needed. Such a taxonomy is described in the following sections.

4.3 Development of the Taxonomy

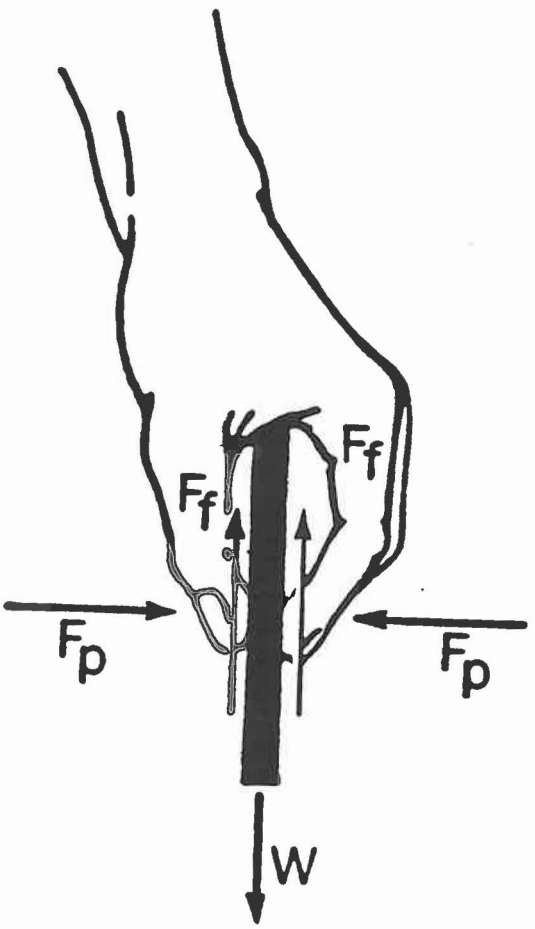
To simplify the characterization of manual force, the proposed taxonomy focused on external forces acting on the hand as opposed to internal forces (e.g., tendon, muscle and joint reaction forces). Although the importance of the latter in the development of cumulative trauma disorders is

acknowledged, their specification and measurement are beyond the scope of this work. Moreover, determination of external forces is necessary for calculating internal forces (e.g., Armstrong 1982; LeVeau 1977; Chaffin and Andersson 1984).

Development of the proposed taxonomy included the following: 1) consideration of the mechanical and physiological aspects of manual force exertion, 2) consideration of traditional work-methods procedures for analyzing work content, 3) a job survey and analysis of selected industrial manual operations to identify forceful elements (therbligs), 4) a mechanical analysis of selected forceful work elements to identify forces acting on the hands, and 5) extension and modification of therbligs to describe forceful exertions.

1. Mechanical and physiological considerations

During work, the hands must overcome resistance from external sources such as gravity (weight), friction, torque, inertia, and the properties of materials that cause them to resist deformation. To slide a box across a table, for example, the hand must exert sufficient force to overcome the frictional force acting at the box/table interface. Similarly, when the hand/object coupling is frictional, the pinch force needed to hold an object is directly proportional to object weight and inversely proportional to the hand/object COF (Fig. 4.1). As force is proportional to



$$F_p = W/(2*COF)$$

Figure 4.1 Pinch force (Fp) is inversely proportional to the coefficient of friction (COF) between the fingers and the object, and directly proportional to object weight (W). Ff = Friction force.

acceleration, the faster one accelerates an object during movement, the more force needed.

When altering the physical characteristics of (i.e., deforming) a material, the hands encounter resistance which is a function of the mechanical properties of the object being deformed, the concentration of applied forces, the efficiency of any tools used, the speed of application of the hand or tool, and the intention/extent of the activity (e.g., to pulverize vs crack). Deformation may be permanent (e.g., grinding or cutting) or temporary (e.g., compressing a spring). Material properties include elasticity (i.e., tensile, compressive, axial and shear strength), bending moment, viscosity, friction between contacting surfaces, and physical structure (e.g., fiber arrangement or grain). For example, more force is needed to hammer a nail into a piece of hardwood than into a piece of soft wood and to stir paint than to stir sugar into water. Tool efficiency is related to the a tool's speed, size, weight, shape, sharpness, and its appropriateness for the task. A drill bit that is designed for steel, for instance, is not appropriate for wood or plastic.

During work, the hands typically encounter resistance from multiple sources. When drilling a hole in a vertical piece of wood, for example, the operator usually exerts an upward force to support the drill, a horizontal (push) force

to advance the drill bit, and counter torque to overcome tool torque reaction forces. The force needed to support the drill is a function of the weight of the tool and any attachments, location of tool center of gravity, and type of hand/handle coupling (i.e., frictional vs normal). If the coupling is frictional, the coefficient of friction (COF) between the hand and the handle is a determinant of required hand force. The amount of push force needed is a function of the resistance encountered by the drill which is proportional to the reaction force of the wood. The latter is related to the hardness of the wood and to tool efficiency. The amount of counter torque needed is related to the drill's torque reaction force and to the handle diameter (length of lever arm).

Physiological: Physiologically, applied hand force is related to sensory feedback, hand moistness, and involuntary neuromuscular responses (i.e., stretch reflexes) induced by tool recoil and tool vibration (Flatt 1961; Westling and Johansson 1984; Radwin *et al.* 1987, 1989; Matthews 1966; Carlsloo and Mayr 1974). Reduced tactile sensitivity, for example, results in increased hand force exertion when individuals are unable to detect and, therefore, respond appropriately to surface frictional conditions (e.g., Mills 1957; Westling and Johansson 1984; Johansson and Westling, 1985). Similarly, since grip force is inversely proportionally to COF, an excessively dry hand can increase

grip force requirements (Comaish and Bottoms 1977; Armstrong 1985). In this case, the cause of the change in COF is physiologic whereas the effect is mechanical. Factors that affect tactile sensitivity include cold temperature (e.g., of the ambient air and the tool), gloves (surface frictional characteristics, thickness, and fit), and vibration (Dusek 1957; Lyman and Groth 1958; Radwin, Armstrong and Chaffin 1987).

Mechanical factors can be distinguished from physiological factors in that the former affect force requirements, whereas the latter affect force actually exerted.

2. **Traditional work-methods procedures**

Traditional work-methods procedures usually break an operation down into its basic components ("therbligs"), such as *reach*, *grasp*, and *move*, to determine the time that should be allowed to perform a task (Barnes 1972; Smith 1978). Once these motion-time elements have been identified, pre-determined time standards can be assigned. Independent variables for time requirements include distance moved, degree of control or accuracy required, object size, shape and weight, condition of the objects (e.g., whether they are jumbled), and restrictions to the path of motion (MTM Association 1974; Smith 1978). The structure of the proposed taxonomy is based on conventional work-methods

procedures; the system can be seen as an extension or modification of traditional therblig analysis techniques.

3. Job survey and analysis

Twenty video-taped manual operations from seven hand-intensive industries (Appendix A) were analyzed to examine the ways in which the hands exert force. This was a convenience sample of operations selected to represent a wide range of common industrial manual tasks. The majority of the operations had been filmed as part of an epidemiologic study which investigated the relationship between forceful exertions and development of CTDs of the upper extremity (Silverstein *et al.* 1987; Armstrong, Fine, and Silverstein 1985; Armstrong *et al.* 1987). The remainder were filmed as part of individual evaluations to identify risk factors requiring ergonomic solutions.

Each selected operation was analyzed in slow-motion using traditional work-methods job analysis procedures (Barnes 1972). The elements ("therbligs") associated with each activity were recorded and those which involved force exertion (i.e., "forceful elements") were identified (Appendix B). Independent variables that could affect the force requirements of each element, i.e., force attributes, were recorded.

The automatic welding operation from the job survey ("Welder," Appendix A) is presented to illustrate application of the taxonomy. Each of the forceful elements from the original job survey was classified in a similar manner (Appendices A and B). The part being assembled is a door liner for an automatic clothes dryer. The job consists of 1) placing a piece of sheet metal into an automatic welding machine (Table 4.1, Steps 1-5), 2) inserting two rectangular metal rods to be welded to the sheet metal (Steps 6-10), 3) simultaneously pressing two spring-loaded palm buttons to actuate the welder (Steps 11-12), and 4) removing the assembled part and setting it aside (Steps 13-16). The hands must overcome gravity forces to move the parts to and from the machine, and to position them in the machine. Thus, these motions are a MOVE. *Force attributes* include weight of the parts, hand/part coupling (frictional vs normal), work pace, and gloves. Since the coupling between the part and the hand was primarily normal, the COF between the part and the hand is not determinant of grip force.

When pushing the buttons to activate the automatic welder, the forces acting on the hand(s) are a function of the stiffness of the spring in the button. The activity is a DEFORM. Force attributes include the mechanical and strength properties of the spring, and the speed with which the force is applied (i.e., momentum of the hand).

Table 4.1 Job analysis of automatic welding operation.

	Description	Force	Work objective
1.	Reach for sheet metal	No	----
2.	Grasp sheet metal	Yes	MOVE
3.	Move sheet metal to welder	Yes	MOVE
4.	Position sheet metal	Yes	MOVE
5.	Release sheet metal	No	----
6.	Reach to rod	No	----
7.	Grasp rod	Yes	MOVE
8.	Move rod	Yes	MOVE
9.	Position rod	Yes	MOVE
10.	Release rod	No	----
11.	Reach to buttons	No	----
12.	Push buttons	Yes	DEFORM
13.	Reach to welded part	No	----
14.	Grasp part	Yes	MOVE
15.	Move part	Yes	MOVE
16.	Release part	No	----

Although both hands performed the same activities, for simplification purposes, the action of only one hand is presented.

3. Mechanical analysis

A mechanical analysis of each force element was done using force diagrams to characterize forces acting on the hands. In an operation called "Hanger," for example, workers transfer steel appliance parts from one conveyor to another. The hands exert reactive (support) forces to overcome the weight of the part (Fig. 4.2). Because the weight of the part is acting normal to the hands, the COF between the hand and the object is not a force determinant.

In a second operation called "Cut-Off," workers use a stationary cutting wheel to disassemble aluminum castings. The worker picks up the part, places it on a table in front of him, and then pushes the part forward against a saw at the end of the table (Fig. 4.3). To get the part, the hands exert upward support force to overcome gravity effects. Factors affecting the amount of support force needed are weight of the part and the type of hand/part coupling, i.e., frictional or normal. Since the coupling is normal, COF between the hand and the part is not a force determinant. Once the part is placed on the table, the hands must exert enough push force to overcome the frictional resistance between the part and the table (Friction force = Weight * COF). As the casting hits the saw, the saw transmits reaction forces to the casting which, in turn, transmits them to the hands. The push forces needed to overcome this additional resistance is a function of the mechanical

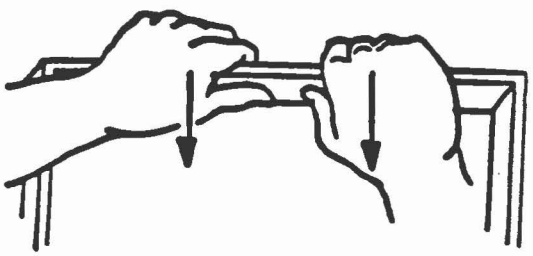
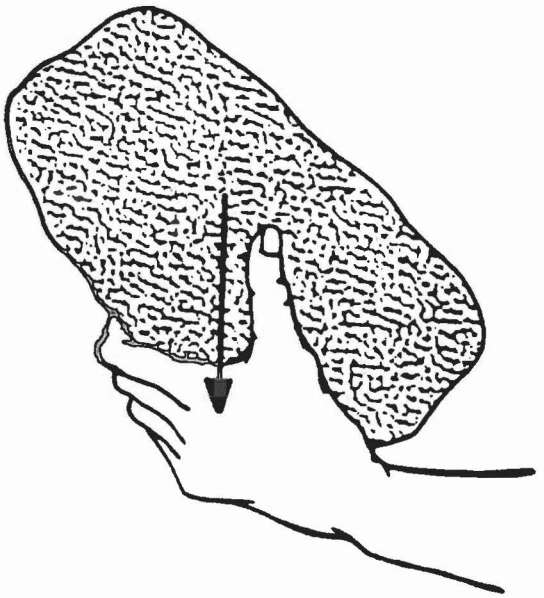
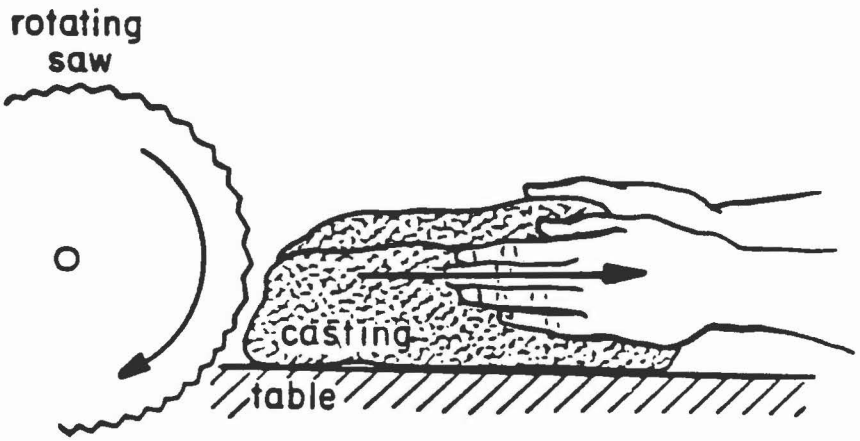


Figure 4.2 Illustration of "Hanger" operation. The worker exerts an upward reactive force to overcome the weight of the part which is acting perpendicular to the hands.



A. Get casting



B. Cut casting

Figure 4.3 Illustration of the "Cut-off" operation. The worker gets the part (A), and then pushes it against a stationary saw located at the end of a table (B).

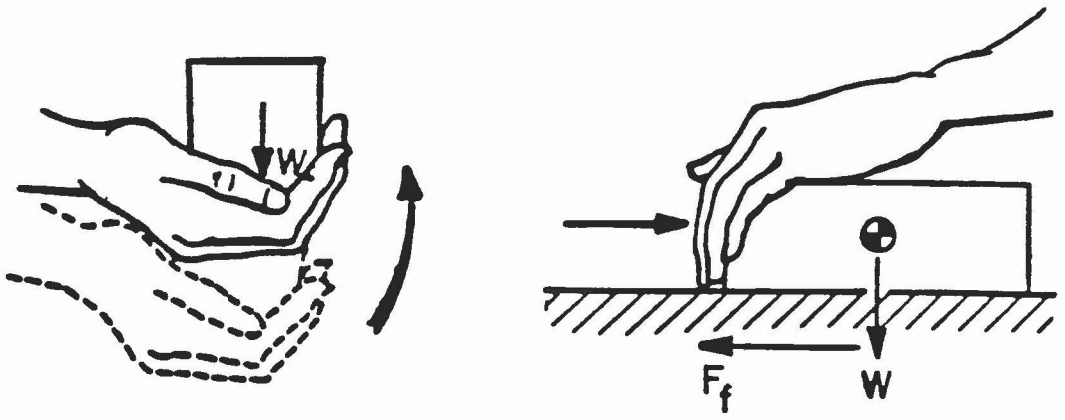
properties of the casting (e.g., hardness), and of saw efficiency (e.g., speed, blade design, sharpness and cross-sectional area of the blade).

4.4 **Work Objectives**

Forceful work elements were classified according to the primary purpose of the activity stated in generic terms (Appendix B). For example, when using a manual screwdriver, the goal is to insert a screw and the primary objective, in generic terms, is to **secure threaded fastener.** Independent variables that could affect the force requirements of each work objective also were identified.

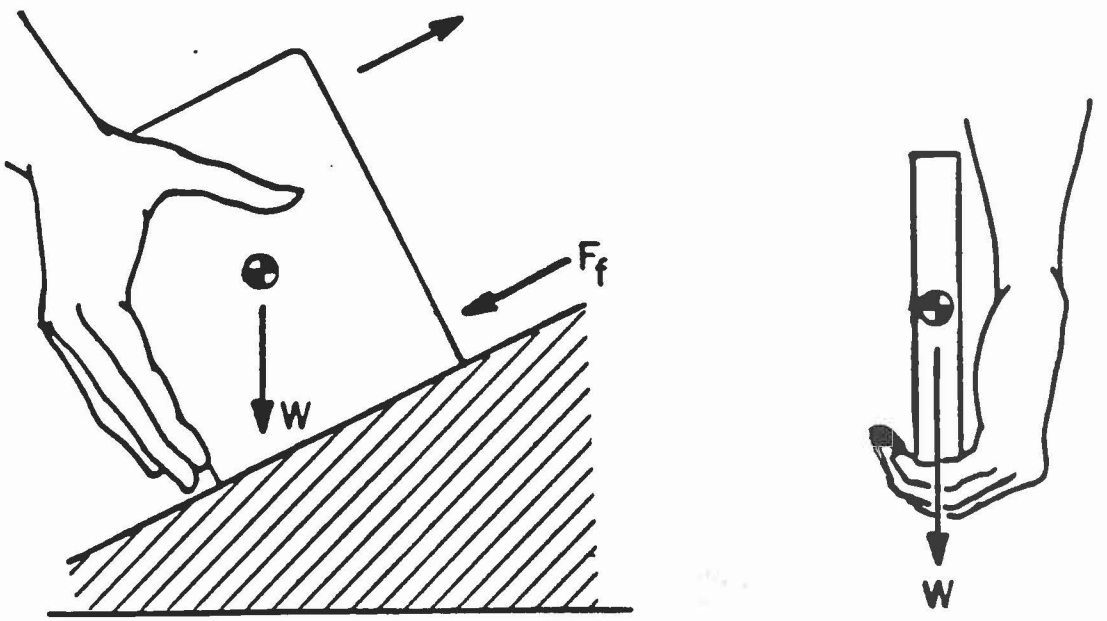
The first four work objectives encompass direct use of the hand, i.e., work done without a tool. The fifth work objective involves tool use and has nine categories to describe specific types of tool actions, such as cutting or grinding.

A. **MOVE.** *Definition*: purpose is to transfer an object from one place to another with or without object support. For example, a box may be transported from one place to another by carrying it (Fig. 4.4a) or by rolling or sliding (Fig. 4.4b). *Examples* are "Core setter," "Eyeletter Cup," and "Welder" from the job survey (Appendices A and B). *Force attributes* for when an object is supported manually



A. MOVE with manual support

B. MOVE without manual support



C. HOLD without manual support

D. HOLD with manual support

Figure 4.4 Illustration of MOVE and HOLD with and without manual support of object. Ff = Friction force.

include the weight of the object and any attachments, the coupling between the hand and the object (frictional or normal), gloves, work pace, and low temperature (i.e., ambient air or object). If the hand/object coupling is frictional, the COF between the hand and the object is a factor. When the object is moved by sliding or rolling (i.e., without manual support), the predominant resistance is friction. The force attributes for sliding/rolling an object are essentially the same as for carrying an object except that object weight is considered in terms of its contribution to inertia and friction force.

B. **HOLD.** *Definition*: to restrain an object with little or no movement. HOLD can occur with or without object support (Fig. 4.4c & 4.4d). *Force attributes* are the same as for MOVE except that work pace is not a factor. *Examples* include holding small parts in one hand for removal and use by the other hand, and preventing an object on a slanted surface from sliding. In the "Circuit Board" operation (Appendix A), the worker held wires in her left hand which she removed with her right hand for insertion into the circuit board.

C. **DEFORM.** *Definition*: To alter the physical characteristics of a material. *Force attributes* include the mechanical and strength properties of the material being altered (i.e., reaction forces of the material), the amount

of material being altered, and how fast force is being applied. *Examples* are pushing palm buttons to activate a press as in the "Punch Press" operation from the job survey (Appendix A), kneading dough, and molding clay.

D. **APPLY TORQUE.** *Definition*: To apply force at a distance from a fixed point causing rotation. *Force attributes* include the length of the lever arm through which the hands or fingers work, amount of resisting torque, and the type of hand/object coupling. If the coupling is frictional, the coefficient of friction between the hand and the object is a factor. *Examples* are turning a knob or valve, tightening a screw or bolt with the fingers, and opening a hinged lid as in the "Wax Injection" operation from the job survey (Appendix A).

E. **USE TOOL.** *Definition*: To utilize a device to accomplish a task. USE TOOL has nine categories to describe commonly-used tools or tool actions. *Force attributes* that may pertain to all eight categories are 1) gloves (e.g., thickness, material, texture) 2) cold temperature (ambient air and tool), 3) hand-held vs stationary, 4) powered vs manual, and 5) orientation of working hand and work surface (e.g., ; horizontal, vertical, or slanted, and low vs high). Typically, a hand-held tool is moved to the part; the work material is stationary. For hand-held tools, **tool weight** is a force variable (attribute). An example of a hand-held

tool is the "Hand Grinder" operation from the job survey (Appendix A). By contrast, for stationary tools, the part usually is moved to the tool, and **part weight** is a factor. For example, in the "Cut-Off" operation (Appendix A), the saw is stationary. The operator gets the part and then slides it up to and against the blade of the saw.

Force attributes for the following nine tool-use categories focus on factors affecting the force needed to engage and control the tool rather than force needed to move or hold the tool. Factors affecting the force needed to support the tool or the part are listed under **MOVE** and **HOLD** above. Tool weight includes the weight of any attachments. Orientation of the work surface (e.g., vertical vs horizontal) determines whether or not tool weight will increase or decrease force requirements.

E.1 **Secure threaded fastener.** *Definition.* To insert or remove threaded fasteners such as bolts and screws. *Examples* of tools are wrenches, pliers, screwdrivers and nutrunners. An example of an operation from the job survey (Appendix A) is "Install Window" using a powered screwdriver. *Task attributes* for forces needed to counteract tool torque reaction forces include 1) length of the lever arm through which the tool or hand works (e.g., handle diameter and length), 2) tool torque reaction forces, and 3) tool shape (e.g., in-line, right angle, or pistol

grip). Tool shape affects a tool's center of gravity, it's moment arm, and the type of hand/tool coupling (i.e., frictional or normal). Variables affecting required push forces include 1) the quality and type of coupling between the tool and the fastener which prevents slipping (e.g., magnetic, depth and width of groove on the head of a screw to prevent slipping, the size of the screwdriver blade relative to the size of the slot in the head of the fastener, screw head configuration [i.e., Phillips vs flat head vs hex head], 2) type of hand/tool coupling (i.e., frictional or normal), 3) tightness of fit between the fastener and the work material (e.g., whether joint is prethreaded or tapped), and 4) mechanical/strength properties of the work material.

E. 2 **Secure non-threaded fastener.** *Definition*: To secure or remove an *non-threaded* fastener such as a rivet, nail, or staple using a pneumatic tool. *Examples* of tools are riveters, hammers and staplers. *Force attributes* include 1) force of tool recoil, 2) mechanical/strength properties of the work material (i.e., the reaction force of the material into which the fastener is being inserted), 3) tool weight, size, and shape, and 4) sharpness and cross-sectional area of the fastener.

E.3 **Cut.** *Definition*: To use an edged device to make a narrow opening in a material to penetrate, separate,

divide, or trim it. *Examples* of tools are scissors, knives, can openers, and saws. An example from the job survey is cutting wires in the "Circuit Board" operation (Appendix A). **Force attributes** include 1) the mechanical/strength properties of the material being cut, 2) the amount and size of the material being cut, 3) tool efficiency (e.g., sharpness of the blade and alignment of scissors blades), 4) cutting technique (e.g., a sawing motion vs a straight push), and 5) appropriateness of the tool for the task.

E.3 **Strike.** *Definition*: To use a device to transmit force to an work material by direct contact for the purpose of 1) altering the shape of the material (e.g., to chop wood or crush stone), 2) driving an object forward (e.g., to hit a nail with a hammer), or 3) creating a sound (e.g., to beat a drum with a stick). An example from the job survey is to use a mallet to "Install window" in a vehicle (Appendix A). *Examples* of striking tools are hammers and sticks (mallets) for playing musical instruments. *Force attributes* are 1) tool handle length, 2) total tool weight and its distribution throughout the tool, 3) intention of the action (e.g., crush vs dent, desired sound level when creating music), 4) angular acceleration and velocity of tool, and 5) mechanical/strength properties of the work material. When driving an object forward as in hammering a nail, the size, shape, strength, and frictional characteristics of the object being driven (e.g., the nail) are important.

E.4 **Grind/Polish.** *Definition*: To alter the physical characteristics of an object by abrasion, e.g., "Hand grinder" (Appendix A). *Examples* of tools are files, grinders, sanders, and buffers. *Force attributes* include 1) the mechanical/strength properties of the work material, 2) the amount of work material, 3) the purpose or extent of the deformation (e.g., a light polishing vs a heavy sanding), 4) tool efficiency (e.g., grit size of sandpaper, condition of grinding surface), and 5) appropriateness of tool.

E.5 **Stretch/Compress.** *Definition*: To apply pressure to a material for the purpose of lengthening or compressing it, or creating a pattern. *Examples* of tools are metal crimpers, embossing seals, and stretching hooks, e.g., for stretching a rubber band or gasket around a fixture. *Force attributes* include 1) size of tool relative to work material (e.g., length of lever arm), 2) coupling between tool and work material (e.g., frictional vs normal and tightness of fit), 3) strength properties (e.g., elasticity) of the material being altered, 4) hand/tool coupling, and 5) speed of application of the tool.

E.6 **Stir/Spread.** *Definition*: To blend, mix, or extend a material such as food, paint, or concrete. *Examples* of tools are spoons, whisks, table knives, paint brushes, spatulas, and hoes. *Force attributes* include 1)

the mechanical properties of the material being worked (e.g., viscosity), 2) the amount of material, 3) tool efficiency and appropriateness, 4) hand/tool coupling, and 5) purpose/extent of the action (e.g., to vigorously whip to incorporate air into a mixture vs gently blend ingredients).

E.7 **Drill.** *Definition*: To make a hole in a material by rotating abrasion using a device that has either a pointed end or an end with a circular, sawlike edge. *Examples* of tools are drills and trephines. *Force attributes* are 1) the mechanical/strength properties of the material being drilled, 2) the amount of material being drilled, 3) hand/tool coupling, and 4) tool efficiency (including the shape, sharpness, and cross-sectional area of the drill bit or cutting edges).

E.8 **Move/Hold.** *Definition*: To transfer or restrain an object with a device. *Examples* of tools are tongs, pliers, clamps, forceps, and eating utensils. *Force attributes* include 1) the size, shape, and weight of the item being held or moved, 2) tool weight and its orientation to the hand, 3) center of gravity of item being held or moved, 4) the type of coupling between the tool and the item being held or moved (e.g., frictional, normal, or magnetic), 5) length of tool (lever arm) if tool is used as a lever, 6) whether the hands maintain the coupling between tool and

part (e.g., by squeezing the handles of the tool), and 7) work pace (when moving).

A summary of the major force attributes for each work objective is presented in Figure 4.5.

4.5 Application of the Proposed Taxonomy: Some Examples

The following examples illustrate application of the taxonomy.

Nutrunner operation: In a right-angle nutrunner operation (Radwin *et al.* 1989), the tool handle is held in the dominant hand while the non-dominant hand pushes against the end near the fastener to engage the tool (Fig. 4.6). The dominant hand exerts 1) an upward reactive (support) force to overcome the weight of the tool, and 2) a reactive force to counteract tool torque as the fastener is tightened. The non-dominant hand exerts a push force to start the fastener and control the tool. In the proposed taxonomy, this activity would be classified as a **USE TOOL: Secure threaded fastener.** Force attributes relative to tool support are the weight of the tool and any attachments, the length of the tool and its center of gravity, and the type of hand/handle coupling (i.e., frictional vs normal). No gloves are worn. Variables affecting push force

Work Objective	Hand/object* coupling	Weight of object or tool	COF between contacting surfaces**	Length of tool or lever arm	Tool center of gravity	Strength properties of work material	Coupling between tool and work material	Torque reaction force	Orientation of working hand/work surface	Intention ***	Velocity/acceleration of applied force	Coupling between fastener and work material	Amount of work material	Tool efficiency	Power vs manual operation	Gloves / Low temperature	Tool recoil	Vibration	Pace
A. MOVE	●	●	●	●	●						●					●			●
B. HOLD	●	●	●	●	●											●			
C. DEFORM						●				●	●		●						
D. APPLY TORQUE	●	●	●	●				●		●						●			
E. USE TOOL																			
1. Secure threaded fastener	●	●	●	●	●		●	●	●	●		●		●	●	●		●	●
2. Secure non-threaded fastener	●	●	●			●	●		●		●		●	●		●	●		●
3. Cut	●	●	●	●	●	●			●	●	●		●	●	●	●	●	●	●
4. Drill	●	●	●	●	●	●			●				●	●	●	●	●	●	●
5. Grind/ Polish	●	●	●		●	●			●	●				●	●	●	●	●	●
6. Compress/ Stretch	●	●	●		●	●	●		●	●				●		●	●		●
7. Stir/ Spread	●	●			●	●			●	●			●	●	●	●	●		●
8. Move/ Hold	●	●	●	●	●		●		●					●	●	●	●		●
9. Strike	●	●	●	●	●	●			●	●	●	●	●	●	●	●	●		●

*Object or tool **Includes hand/object COF ***Includes desired tightness of fit

Figure 4.5 Force attributes for each work objective.

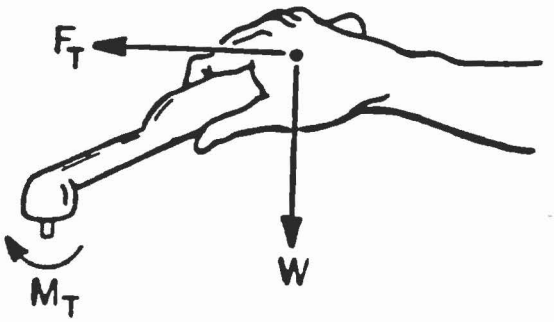
requirements are the strength properties of the work material, the quality of the coupling between the fastener and the tool (i.e., to prevent slipping), the spatial orientation of part being worked, and the quality of the interface between the fastener and the work material (e.g., size of the hole relative to the size of the fastener and pre-threaded vs self-tapping joint). Factors affecting the force needed to counteract tool torque reaction force are tool torque output, length of the lever arm (e.g., tool length or diameter), and coupling between the hand and the tool handle (i.e., frictional vs normal).

Meat cutting: Meat cutting would be classified in the proposed taxonomy as **USE TOOL: Cut.** Force attributes include knife efficiency (e.g., blade sharpness and cross-sectional area), material properties of the meat as they affect the resistance encountered (e.g., internal temperature, gristle), low environmental temperature (may numb the hands and result in overgripping), gloves (affect the frictional characteristics of the hand/handle interface and tactile sensitivity), size and shape of the knife (e.g., affects hand/handle coupling), and cutting technique (e.g., sawing, ripping, vs pushing and pulling).

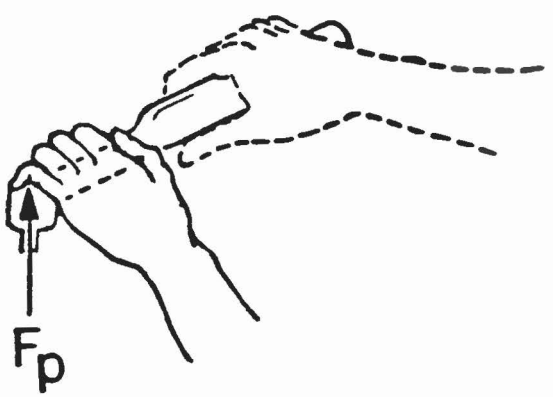
4.6 Discussion

The structural basis of the proposed taxonomy is the primary work objective of the forceful elements of a manual task. Conceptually, the structure is similar to that of predetermined time systems which predict performance times for industrial tasks. Such systems typically divide tasks into basic motion-time elements (e.g., Reach, Grasp, Move) or combinations of motions (e.g., Get), and assign standard time units to them. These time units are based on independent variables that affect performance times, e.g., distance moved and precision required (Karger and Bayha 1977, p. 204). Similarly, for the proposed taxonomy, variables that may affect force requirements (i.e., force attributes) of manual actions involving force have been identified, e.g., object weight and tool torque reaction force.

Principal factors affecting hand force: Although the proposed taxonomy (Fig. 4.5) attempts to identify all the forces acting on the hands and the relevant independent variables, it does not indicate which of attributes contribute the most to required hand force. In some cases, this is apparent from knowledge of the task, e.g., weight of the part. One of the tasks in the "Circuit Board" operation, for example, involves cutting wires with a small, light-weight pair of hand-held clippers. The activity would



A. Forces acting on the right hand.



B. Forces acting on the left hand.

Figure 4.6 Illustration of the forces acting on the hands during a simulated right-angled nutrunner operation. Mt = spindle torque; W = tool weight; Ft = torque reaction force against the hand; Fp = push force to start the fastener and to keep the bit engaged.

classified as a **USE TOOL: Cut.** Reactive hand force is exerted to support the clippers, and to overcome the reactive force of the wires. Force attributes affecting support forces are tool weight, shape, and type of hand/tool coupling. The size of the clippers is such that they can be held in the palm with the fingers wrapped around the handles. In this posture, the hand/handle coupling is normal, and, therefore, the COF between the hand and the handles is not a force determinant. Factors affecting the amount of grip force needed to overcome the reaction force of the wires are the amount and strength characteristics of the wire, the sharpness and cross-sectional area of the clipper blades, and mechanical advantage of the tool. For practical purposes, since tool weight is negligible, the force attributes for to this component of hand force could be ignored. The critical force component of this hand activity, therefore, is the squeeze force needed to overcome the resistance of the wire to deformation. Therefore, only factors that affect this squeeze force need be considered. Similarly, Radwin *et al.* (1989) found that peak tool torque reaction forces accounted for over 97% of the resultant peak hand force during a simulated right-angle nutrunner operation. Tool support forces were insignificant.

The force attributes identified in the proposed taxonomy were emphasized because they are measurable or observable, and usually can be controlled by job and tool

design. Although it is recognized that behavioral factors such as muscular tenseness, voluntary effort, and attentiveness, also affect applied force, their discussion is beyond the scope of this work.

The proposed taxonomy can be used for job analyses to identify the forceful attributes of manual tasks, and to evaluate the effectiveness of ergonomic interventions to relieve these stresses. The taxonomy also provides a framework for collecting and organizing quantitative data relating to the force requirements of manual tasks. Ultimately, the taxonomy may serve as a foundation for the development of a standard data system for manual force similar to those currently available for time.

In addition, the proposed taxonomy provides a common terminology that can facilitate comparison of results of studies of manual force, and aid the development of a data base for the force requirements of generic manual tasks. This information eventually could help establish quantitative guidelines for reducing force requirements. Such a data base also would provide needed information to establish dose-response relationships between force and cumulative trauma disorders.

4.7 Summary and Recommendations

This paper describes the development of a taxonomy for classifying the forceful elements of manual work. The structural basis of the proposed taxonomy is the generic work objective of the hand activity. The first four objectives apply to direct use of the hand(s): MOVE, HOLD, APPLY TORQUE, and DEFORM. The fifth objective, USE TOOL, has nine categories for describing the actions of commonly-used tools. Force attributes, the independent variables that affect the force requirements of each objective, are identified and discussed.

Further work is needed to test the reliability and exhaustiveness of this taxonomy. This could be done by instructing several analysts in the use of the taxonomy, having them apply it to new set of jobs from a variety of hand-intensive industries, and comparing their results.

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4.9 Appendix A. Description of operations from job survey.

INDUSTRY	JOB DESCRIPTION
Electronics	**Circuit board:** Insert wires into slots in board, clip and solder them
	Buffing: use stationary buffing wheel to smooth plastic parts
	Eyeletting Handle/Eyeletting Cup: feed small parts into punch machine (2 operations)
Major appliance manufacture	**Punch Press:** load large metal blanks into punch press
	Hanger: transfer parts to and from moving overhead racks
	Welder: load clothes dryer parts into automatic welding machine
Investment casting	**Wax - injection:** remove formed wax part from mold
	Hand grinder: use small hand grinder to remove burrs from metal castings
	Cut-off: use stationary cutting wheel to disassemble metal casting
	Core Press: clean press with compressed air hose
	Guaging: use stationary gauges to check part specifications
Apparel manufacture	**Belt loop:** position (stretch and hold) jeans for machine attachment of belt loops
	Spreader: spread multiple layers fabric onto table by pushing on bolt of fabric suspended on overhead horizontal rod
	Cutter: use automatic cutter to cut pattern through multiple layers of fabric

Appendix A (cont'd)

Iron foundry	**Hand grinder:** use small grinder to remove sprue from metal casting
	Core setter: place sand cores into mold on moving conveyor line
Furniture manufacture	**Hand sander:** use hand-held air-powered sander to sand table top
Vehicle manufacture	**Sewing machine operator:** assemble upholstery for vehicle
	Install window: install window in vehicle using mallet and driving wedge plus air - powered screw driver

4.10 Appendix B. Classification of forceful work elements of operations from job survey.

Operation	Description of Activity	Therblig	Generic Work Objective
Buffing	Get part	R, G, M	MOVE
	Polish part	M, P	USE TOOL: Grind/Polish
Cut-off	Get part	R, G, M	MOVE
	Cut part	M, P	USE TOOL: Cut
Core-Press	Get hose	R, G, M	MOVE
	Use hose	M, P	MOVE
Hand grinder	Use grinder	M, P	USE TOOL: Grind/Polish
Core setter	Get part	R, G, M	MOVE
	Place part in mold	M, P	MOVE
Circuit board	Use clippers	M, P	USE TOOL: Cut
	Use soldering iron	M, P	MOVE*
Eyeletter cup	Get part	R, G, M	MOVE
	Place part in plunger	M	MOVE
	Push plunger	M	DEFORM
Wax-injection	Get mold	R, G, M	MOVE
	Open hinged lid	R, G, M	APPLY TORQUE
	Get part	R, G, M	MOVE
Install window	Use mallet	M	USE TOOL: Strike
	Use power screwdriver	M, P	USE TOOL: Secure threaded fastener
Guaging	Get part	R, G, M	MOVE
	Gauge part	M, P	MOVE

Appendix B (Cont'd)

Hanger	Get part	R, G, M	MOVE
Welder	Get part	R, G, M	MOVE
	Position part	P	MOVE
Punch press	Get part	R, G, M	MOVE
	Position part	M, P	MOVE
	Push buttons	R, M	DEFORM
Automatic cutter	Use cutter	R, G, M	USE TOOL: Cut
Spreader	Spread fabric	R, G, M	MOVE
Hand sander	Use sander	M, P	USE TOOL: Grind/Polish
Sewing machine operator	Feed fabric into sewing machine	M, P	MOVE
Eyeletter handle	Get part	R, G, M	MOVE
	Place part in machine	M, P	MOVE
Belt loop	Get material	R, G, M	MOVE
	Position material	M, P	DEFORM

R = Reach; P = Position; M = Move; G = Grasp (Barnes 1972).

*Tool use is classified as a MOVE because metal deformation takes place via heat rather than by mechanical force.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Integration of Research

The research presented in this dissertation provides a foundation for the development of a methodology for determining the force requirements of manual tasks. The first two experiments (Ch. 2) investigated how much of the variation in pinch and grip force could be accounted for using a combination of selected task and personal factors. The results indicated that, although significant amounts of variation in pinch and grip force could be accounted for (primarily by load), the majority of the variation in performance data remains to be explained. Some suggestions for explaining additional variation in performance data were presented.

Results of the third laboratory study (Ch. 3) indicated that the COF effect on pinch force, which was not significant in the first study of pinch force (Ch. 2), was load-dependent. The practical implications of this finding are that high-friction handles will be most effective at

reducing force exerted for heavy objects. The results of Chapters 2 & 3 are relevant to tool design and job analyses, and may be useful in the design of future studies of manual force.

When the average exerted forces for the various loads in the three experiments (Chapters 2 & 3) was compared, pinch force appeared to be a more linear function of load than grip force (Fig. 5.1). This finding may be attributed, in part, to the range of loads over which pinch force was evaluated. Specifically, pinch force was evaluated at near maximal weights whereas grip force was evaluated at much lower strength levels. It would be instructive to evaluate the relationship of grip force to load force at loads requiring nearer maximal grip strength.

Finally, in Chapter 4, a taxonomy for describing and classifying the forceful aspects of manual tasks was developed to facilitate the collection and organization of needed quantitative force data. The proposed taxonomy may be useful in the design of future studies of manual force. Also, by providing common terminology, the taxonomy may help compare the findings of different investigators. Further, the proposed taxonomy can serve as a foundation for development of a standard data system for determining force requirements, similar to those available for determining time standards.

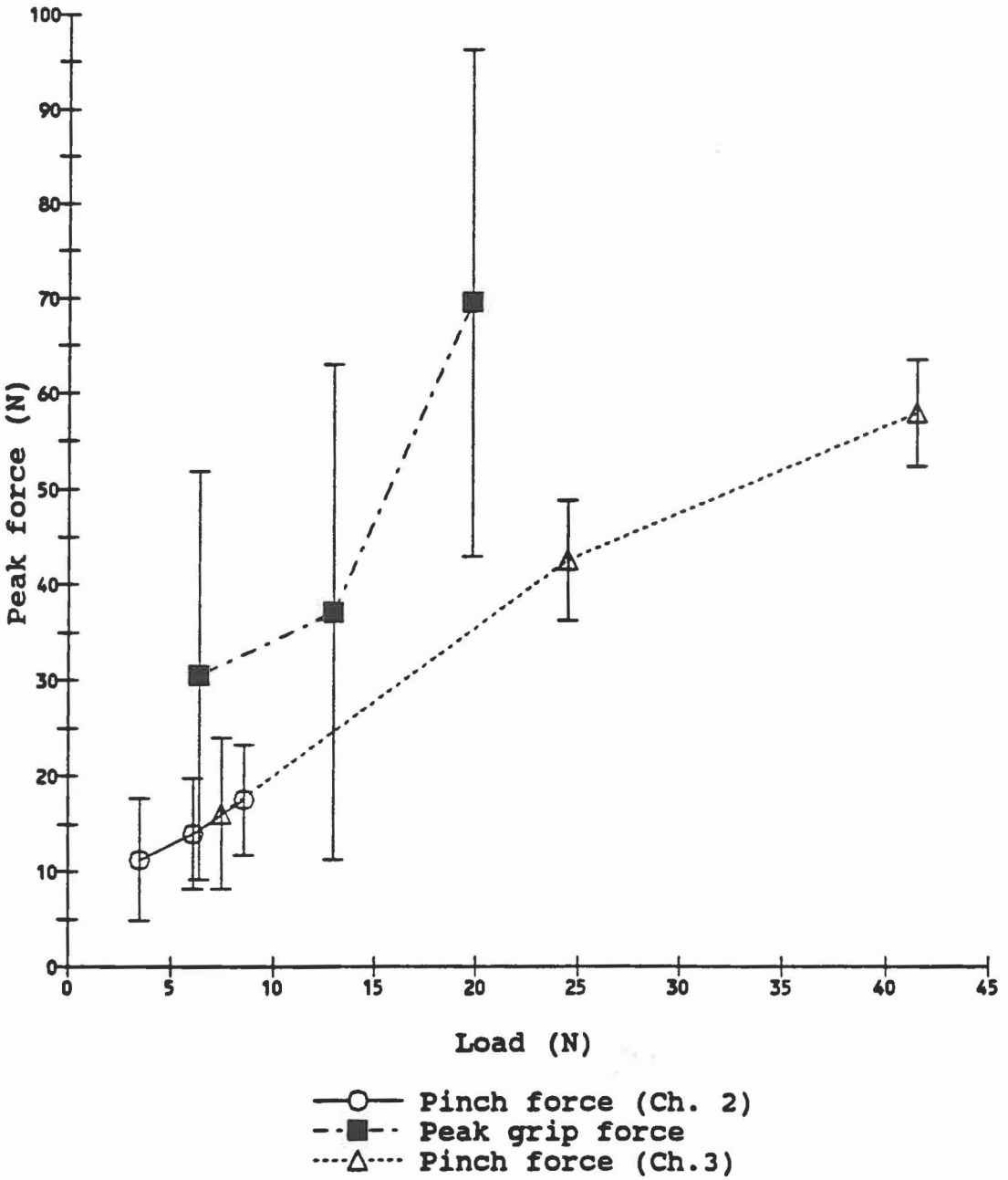

Figure 5.1 Combined peak pinch and grip force data.

5.2 Recommendations

1. Future studies of grip and pinch force in which work pace is a factor should consider designs that minimize inter-subject variability in movement time. For example, a wide interval of paces could be used, or an incentive system in which one group works "as fast as (they) can" and another group works at a "comfortable" pace. Differences in force exertions between externally-paced and self-paced groups of subjects also should be compared.

2. Future studies of grip force, i.e., using a power grip, should evaluate the effect of COF and weight at near maximal loads.

3. Future studies of grip and pinch force should consider using at least two simultaneous methods for estimating manual force, e.g., electromyography (EMG) plus strain gage-instrumented devices, or strain gage devices plus force-matching to determine their correlation.

4. Further work is needed to refine and test the reliability and exhaustibility of the proposed taxonomy. A suggested approach is to a) develop a user's manual, b) instruct a number of analysts in the use of the taxonomy, c) have the trained analysts apply it to new set of jobs

from a variety of hand-intensive industries, and d) compare the results of the various analysts.

5. A series of laboratory experiments should be done to determine the force requirements of generic manual tasks using the proposed taxonomy as a guide.