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Evaluation of Periodontal Scaling Task and Development of Force-Endurance Models for Simulated Scaling Task

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EVALUATION OF PERIODONTAL SCALING TASK AND DEVELOPMENT OF FORCE-ENDURANCE MODELS FOR SIMULATED SCALING TASK

by

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EVALUATION OF PERIODONTAL SCALING TASK AND DEVELOPMENT OF FORCE-ENDURANCE MODELS FOR SIMULATED SCALING TASK

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Force exertion is critical in grasping and holding activities at sub-maximal levels. Exertion misjudgments lead to musculoskeletal disorders (MSDs) impairing performance and productivity. Published literatures on grasping have addressed the force balance and endurance issues for non-prehensile movements of hand. However, little information is available on the force exerted in precision gripping employed in health care. Professionals, especially dental hygienists, when treating patients adopt awkward postures for extended period leading to cumulative trauma. Literatures on cumulative trauma have identified force exertion to be an important risk factor. Lack of information on fatigue with precision gripping motivated this research to establish force-endurance relation for simulated dental task.

A preliminary study was performed to estimate the force exerted during sub-maximal three-jaw chuck pinch and maximal three-finger pencil-hold tasks. Exertions were recorded with force sensing resistors (FSR). The tasks were evaluated for four hand conditions: Bare hand, Vinyl, Latex and Nitryl gloves. Results from the preliminary study provided directions to investigate the fundamental research question of how long can dental professional exert and hold using modified pencil-hold before fatiguing. This research question was addressed by developing a mathematical relation between force exertions and time for a simulated dental task. Periodontal scaling was identified as the

representative healthcare task and five participants performed the simulated scaling task on a typodont. The average scaling force was found to be 53.95% of maximum voluntary contraction (MVC). A limiting exertion level of 40%MVC was established for the development of force-endurance relation to accommodate the average scaling force exertion.

Mathematical prediction equations for endurance times were developed and validated using the data from a total of sixty participants that included 30 experts and 30 novices. Similarly, relation between perceived and actual force exertions were developed and validated. The force-endurance models and the relations between perceived and actual exertions were found to follow a third-order polynomial. This research is first of its kind on precision grasps used in dentistry whose implications and recommendations have been discussed.

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List of Tables

List of Figures

Table of Contents

CHAPTER I

Introduction

1.1 Problem Introduction

Humans perform daily tasks ranging from simple grasps to complex dexterous activities with hands which make the human hand an important natural tool for task performance. These daily tasks are physically demanding and may cause cumulative trauma with overuse affecting performance efficiency. United States Bureau of Labor Statistics (BLS) reports that cumulative trauma accounted for 29% of all workplace related injuries in 2008 of which 17% of the reported cases were in healthcare profession. Forceful exertions coupled with repetitive action in awkward postures have been identified as potential risk factors for cumulative trauma.

Healthcare professionals, particularly dental professionals, employ forceful repetitive exertions using awkward wrist angles in stooped postures leading to work-related musculoskeletal disorders (Anton et al 2002). Published literatures on dental profession have identified that low back, neck and shoulders are the common sites of musculoskeletal disorders (Macdonald et. al., 1988; Osborn et. al., 1990; Liss et. al., 1995; Lalumandier and McPhee, 2001). Similarly, carpal tunnel syndrome (CTS) has been reported the common hand related trauma among dental hygienists (Lalumandier and McPhee, 2001). According to Bureau of Labor Statistics data, dental hygienists ranked first among all occupations in the proportion of cases of CTS per 1000 employees (Leigh and Miller, 1998). Dental hygienists are at a higher risk because their tasks are demanding, warranting precision and prolonged exertion on the small cylindrical tools used when treating patients.

The small specialist tools are held and manipulated within the compass of the fingers of the dental professionals who mandatorily use gloves. Gloves protect the professional from harmful pathogens that are present in the body fluid of the patients. The use of gloves affects the tactile feedback critical to force exertions. This is compensated with overexertion or under exertion resulting in forceful exertions for an extended period, and the misjudgment of exertion levels lead to muscular fatigue.

Published literatures on static strength and endurance time presented contradictory results. For example, Rohmert (1960) identified 15%MVC as the endurance limit for human static strength that was contradicted by Garg et al (2002) who established 5%MVC as the endurance limit for shoulder girdle. The conflicting results coupled with the limited information on force exertions for precision gripping tasks motivated this research to investigate the endurance time for dental tasks as they involve forceful pinching in awkward postures. The results will benefit the dental professionals as the endurance limit will allow engineers to develop ergonomic interventions to alleviate musculoskeletal disorders.

1.2 Scope for this Research

Currently a gap in the literature exists to answer the fundamental question of how long should the dental professional work before fatiguing. This research attempts to answer the question by establishing a force-endurance model for modified pencil-hold. Modified pencil-hold is the type of grasp commonly employed by the dental professionals to hold the tool within the compass of the thumb, index and middle fingers. Gloves being an integral part of the dental tasks, separate force-endurance models will be developed for glove conditions.

1.3 Chapter Outline

The rest of this dissertation is provided in five chapters. The main body of this dissertation begins with Chapter 2 where summary of the literatures on hand capabilities, strength, dexterity, endurance time, sub-maximal hand performances, endurance models, and dental tasks are presented. Chapter 3 provides the research rationale, scope of this dissertation, research objective and description of the research hypotheses. Chapter 4 presents the research methodology including the preliminary study, force-time capturing procedure, data trimming logic, force-endurance modeling, relation between the perceived and actual forces and model validation. Chapter 5 provides a description of the study results. In the last chapter, discussions of the study results, overall discussions, direction for future research, conclusions, and recommendations from this dissertation are listed.

CHAPTER II

Background Literature

This chapter discusses the available literatures on hand capabilities, grip strength, endurance, and dental tasks.

2.1 Human Hand

Human hand is the most versatile tool that is used to perform daily activities from simple grasping to complex manipulation of objects. In performing these tasks, hand movements are categorized into prehensile and non-prehensile movements (Napier 1956). In the prehensile hand movement, the object is seized and held partly or wholly within the compass of the hand. The non-prehensile movement involves manipulation of objects by pushing or lifting motions with the whole hand or by individual fingers.

Landsmeer (1962) further analyzed Napier’s findings and grouped human grasping into power grips and precision handling. The author identified that power grips involve a dynamic phase that included opening of hand, positioning of fingers and grasping of objects, and a terminal static phase characterized by rigid relational movement of the grasped object with respect to wrist, elbow or shoulder. He claimed the use of the term “handling” when objects are held and manipulated within the compass of fingers (precision) as it did not involve the distinguishable static phase of power grips.

A sense of critical balance of force is required in both power grip and precision handling that can be affected by friction, object weight and individual safety margins (Westling and Johansson, 1984). This sense of critical balance is important for human performance as excessive force will lead to muscular fatigue or less force will lead to unsafe handling of objects.

2.2 Hand Capabilities on Strength and Dexterity

This section of the chapter summarizes the published literatures on hand strength capabilities and hand dexterity. The focus of these published literatures is the evaluation of performance variance with glove use.

2.2.1 Literatures on Strength Performances

Cochran, Albin, Bishu, and Riley (1986) examined differences in grasp force degradation among five different types of commercially available gloves as compared to a barehanded condition. They found that the force exerted with bare hands was significantly higher than the grasp forces with any glove condition. Similarly, Bishu et al (1987) investigated strength performances based on tenacity, snugness and suppleness of three different gloves. They found that coefficient of friction (tenacity) was an important performance determinant with glove use. Wang, Rodgers, and Bishu (1987) performed an experiment on strength decrements with three different types of gloves. The authors showed that there was a reduction in grip strength when comparing gloved performance to barehanded performance.

Later, Bishu et al (1993) examined human hand capabilities with Extra Vehicular Activity (EVA) gloves at different pressures. They evaluated three types of EVA gloves at five pressure differentials for grip strength, dexterity and manipulability. They found that EVA gloves also reduced strength performance by 50% and identified hand performance reduction with increasing pressure differential.

Kinoshita (1999) examined the effect of glove on spatiotemporal characteristics of prehensile forces. The author evaluated the surgical glove of varying thickness (0.24, 0.61, 1.02 mm) on a slippery rayon surface and found that glove thickness modified the cutaneous sensation which influenced grip force. An interesting finding from this study was that subjects maintained a low grip force with rubber gloves. The author claims that rubber gloves provide better efficiency of force and temporal control in precision handling of small objects. The findings from Kinoshita (1999) were support by a later research by Shih et al (2001) who evaluated the effects of latex gloves on the kinetics of grasping. The authors found that tactile sensitivity was impaired with multiple layers (one, two or three) of gloves which were evaluated using the two-point discrimination test and Von-Frey hair test. The authors also found that subjects exerted more force to lift different weights (100, 150 and 200 g) with different layers (one, two or three) of gloves. Similarly, Longo, Potvin and Stephens (2002) used a psychophysical methodology to quantify maximum acceptable forces during repetitive thumb insertions with J-clip and push-pin end effectors. The authors captured one hour of data from eleven female participants who performed the task on a simulated device at a rate of seven exertions per minute with 4 seconds break between exertions with gloves being used for 10 minutes. They identified that the participants exerted 22% more force with gloves. Similarly, Imrhan and Farahmand (1999) examined the effect of handle characteristics and dry and grease smeared gloves on tightening torques in simulated oilrig tasks. They found a 50% reduction of torque with grease smeared gloves as compared to dry gloves. They also reported a 15% increase in torque with long handles compared to the short one; a 25% increase with the medium diameter handle compared to the small one; and a 12% increase with the horizontally oriented handle compared with the vertical one.

Sudhakar et al (1988) evaluated the effect of rubber and leather gloves on grip strength using electromyography. They found no significant differences in muscle activities across gloved and bare hand conditions establishing that certain amount of force is lost at the hand-glove interface. McMullin and Hallbeck (1991) reported a decrease in force exertion when the maximal power grasp was evaluated at neutral, 45^0 extension, 45^0 flexion, and 65^0 flexion of the wrist position. Their findings were consistent with the results of Putz-Anderson's (1988) who determined that maximum force was recorded at neutral position followed by 45^0 extension, 45^0flexion and 65^0 flexion in order.

2.2.2. Literature on Dexterity and Tactile Performance

Dexterity and tactility are also critical to perform daily tasks that have been evaluated in many hand performance researches. Banks and Goehring, (1979), while studying the effects of degraded visual and tactile information in diver performance, found that the use of gloves increased task time by 50-60 percent. McGinnis, Bensel and Lockhar (1973) investigated the effect of six different hand conditions on dexterity and torque capability. They used bare hand, leather glove, leather glove with inserts, impermeable glove, impermeable glove with inserts and an impermeable glove with built in insulation. They found that under dry conditions, the impermeable glove had the best torque capability, and that the barehanded dexterity performance was superior to that of gloved hand performance.

Plummer et al. (1985) studied the effects of nine glove combinations (six double and three single) on performance of Bennett Hand Tool Dexterity Test apparatus. Results of the study indicated that subjects, with gloves donned, took longer times to complete the task, with the double glove causing longer completion times. Cochran and Riley (1986) found that gloves generally reduce dexterity and force capability.

Bensel (1993) conducted an experiment to evaluate the effects of three thicknesses (0.18 mm, 0.36 mm, 0.64 mm) of chemical protective gloves on five dexterity tests: Minnesota rate of manipulation turning; O'Connor finger dexterity test; cord and cylinder manipulation; Bennet hand tool dexterity test; and rifle disassembly/assembly task. Mean performance times were shortest for the barehanded condition and longest for the thickest (0.64 mm) glove.

Nelson and Mital (1994) found no appreciable differences in dexterity and tactility among latex gloves of five different thicknesses: 0.2083 mm; 0.5131 mm; 0.6452 mm; 0.7569 mm; and 0.8280 mm. The authors found the thickest latex glove (0.8280 mm) to be puncture resistant, with no loss in dexterity and tactility as compared to the thinner gloves.

Bollinger and Slocum (1993) investigated the effect of protective gloves on hand movement and found that gloves decreased the range of motion in adduction/abduction and supination / pronation while extension/ flexion were not affected. Their findings suggest that there is an overall reduction in the kinematic abilities of the hand while wearing gloves.

Geng et al (1997) studied the effect of gloves on manual dexterity in cold (+19°C and -10° C) environments. They compared four different gloves and two different gloving (outer and inner) for bolt-nut and pick-up tasks. They found a significant difference in performance between the gloves in bolt-nut task. They also found that outer-inner combination gloving may be an approach to use for precision tasks.

Desai and Konz (1983) studied the effect of gloves on tactile inspection performance, and found that gloves had no significant effect on the inspection performance. In fact, they recommend that gloves be worn during tactile inspection tasks to protect the inspectors' hands from abrasion, and to help in the detection of small surface irregularities. Nelson and Mital (1994) found no appreciable differences in dexterity and tactility among latex gloves of five different thicknesses.

Geng et al (1997) investigated the tactile sensitivity of gloved hand in a cold (-12°C and -25°C) operation. They measured the tactile performance using an identification task with various sizes of the objects over the percentage of misjudgment. They found that both the gloves and hand/finger cooling affected tactile performance. They also identified that the effect of object size on tactile discrimination was significant and the misjudgment increased when similar sized objects were identified at -25°C

Madhunuri and Bishu (2005) determined the effect of latex and vinyl gloves on hand performance. They developed a new test (Sponge test) to measure fine finger tactility. They found that tactility, dexterity and strength were better when subjects donned latex gloves than vinyl gloves. Results from functional tests showed that ability to perform was better when subjects donned latex gloves than vinyl gloves. However, the results showed that vinyl gloves generated less sweat than latex gloves.

2.2.3. Literatures on Sub-maximal Exertion, Fatigue and Endurance Time

Most tasks require a sustained level of force exertion. The ability to sustain continuous dynamic contraction or isometric contraction for a prolonged period of time is defined as endurance. Endurance limit is defined as the %MVC below which static muscular work or a posture can be maintained without fatigue irrespective of its duration (Rohmert, 1973). Rohmert (1960) established a 15%MVC as the endurance limit in his generic cubic relation between the human static strength and endurance time. This 15%MVC endurance limit was argued by other researchers (Garg et al 2002, Björksten and Jonsson, 1977, and Jorgensen 1988) who developed different force-endurance models that were specific to body part studied. Garg et al (2002) evaluated the endurance time for shoulder girdle using 12 females for 5 different postures at seven different %MVCs. He established a power model which did not become asymptotic even at 5%MVC. They claimed that Rohmert's cubic relation overestimated endurance time for %MVCs that were < 45% and underestimated the endurance time for %MVCs that were >45%. Similarly, Deeb and Bishu (1991) developed an exponential relation between the force exerted and the endurance time when eight male participants exerted 10, 20, 30, 40, 50, 60, 70, 80 90, and 100%MVC on a Lafayette hand dynamometer. Similar exponential relation was developed by Bishu et al (1994) when they evaluated three types of extra-vehicular activity gloves. Different force-endurance models have been developed (Table 2.1) to establish the maximum endurance time (Ahrache et al 2006).

Table 1 List of Force-Endurance Models

No	**Model**	**Standardized formulation (MET in minutes)**	**Number of subjects**
General models			
1	Rohmert (1960)	$\mathrm{MET} = -1.5 + \frac{2.1}{\mathrm{fMVC}} - \frac{0.6}{\mathrm{fMVC}^2} + \frac{0.1}{\mathrm{fMVC}^3}$	38
2	Monod and Scherrer (1965)	$\mathrm{MET}=0.4167\times(\mathrm{fMVC}-0.14)^{-2.4}$	(*)
3	Huijgens (1981)	$\mathrm{MET} = 0.865 \times \left[\frac{1-\mathrm{fMVC}}{\mathrm{fMVC}-0.15}\right]^{1/1.4}$	(*)
4	Sato et al. (1984)	$\mathrm{MET}=0.3802\times(\mathrm{fMVC}-0.04)^{-1.44}$	5
5	Manenica (1986)	$\mathrm{MET}=14.88\times\exp(-4.48\mathrm{fMVC})$	18
6	Sjogaard (1986)	$\mathrm{MET}=0.2997\times\mathrm{fMVC}^{-2.14}$	(*)
7	Rose et al. (1992) (General)	$\mathrm{MET}=7.96\times\exp(-4.16\mathrm{fMVC})$	8
Shoulder (Equivalent number of subjects : 64)			
8	Sato et al. (1984)	$\mathrm{MET}=0.398\times\mathrm{fMVC}^{-1.29}$	5
9	Rohmert et al. (1986) (Posture 1)	$\mathrm{MET}=0.2955\times\mathrm{fMVC}^{-1.658}$	7
10	Mathiassen and Ahsberg (1999)	$\mathrm{MET}=40.6094\times\exp(-9.7\mathrm{fMVC})$	40
11	Garg et al. (2002)	$\mathrm{MET}=0.5618\times\mathrm{fMVC}^{-1.7551}$	12
Elbow (60)			
12	Hagberg (1981)	$\mathrm{MET}=0.298\times\mathrm{fMVC}^{-2.14}$	9
13	Manenica (1986)	$\mathrm{MET}=20.6972\times\exp(-4.5\mathrm{fMVC})$	18
14	Sato et al. (1984) (Elbow)	$\mathrm{MET}=0.195\times\mathrm{fMVC}^{-2.52}$	5
15	Rohmert et al. (1986) (Posture 2)	$\mathrm{MET}=0.2285\times\mathrm{fMVC}^{-1.391}$	7
16	Rose et al. (2000)	$\mathrm{MET}=20.6\times\exp(-6.04\mathrm{fMVC})$	13
17	Rose et al. (1992) (Elbow joint)	$\mathrm{MET}=10.23\times\exp(-4.69\mathrm{fMVC})$	8

No	Model	Standardized formulation (MET in minutes)	Number of subjects
Hand (18)			
18	Manenica (1986) (hand grip)	$MET=16.6099\times\exp(-4.5fMVC)$	18
Back/Hip (Total number of subjects and situations 75)			
19	Manenica (1986) (body pull)	$MET=27.6604\times\exp(-4.2fMVC)$	18
20	Manenica (1986) (body torque)	$MET=12.4286\times\exp(-4.3fMVC)$	18
21	Manenica (1986) (back muscles)	$MET=32.7859\times\exp(-4.9fMVC)$	18
22	Rohmert et al. (1986) (posture 3)	$MET=0.3001\times fMVC^{-2.803}$	7
23	Rohmert et al. (1986) (posture 4)	$MET=1.2301\times fMVC^{-1.308}$	7
24	Rohmert et al. (1986) (posture 5)	$MET=3.2613\times fMVC^{-1.256}$	7

From the above table it is evident that the relation between force exertions and maximum endurance time were mostly power or exponential functions. The common finding from the published literatures is that force and endurance times were characterized by the task. Another finding is that personal protective equipments, gloves in particular, affect force endurance. For example, Bronkema and Bishu (1996) investigated the effect of friction on grasp force by applying two different sizes of silicone pads to glove surface. They identified that the application of silicon to the surface of the glove significantly affects the peak and stable holding force, with the ratio of peak to stable force reducing with increasing friction. In a different study, Buhman et al (2000) examined the grasp force at maximal and sub-maximal exertion and identified that grasp force was affected by frictional and tactile feedback. They found that the glove effect was strong at maximal exertions but marginal at sub-maximal exertions. From the findings they conclude that the neuro-muscular mechanisms utilized during maximal exertions are differentially applied and/or different from those used during sub-maximal or 'just holding' types of exertion.

Similarly, Shih (2007) investigated the effects of gender and glove on hand fatigue by measuring the reduction in grip strength, shift in time needed to reach MVC and the maximum endurance time. The author found a significant gender effect on the endurance with males having longer endurance and a greater reduction in the grip strength than females. Chang and Shih (2007) evaluated the effect of glove thickness on fatigue during five second and sustain gripping tasks. The authors found that glove usage did not affect the degeneration of MVC and the maximum endurance time. This result contradicts the previous literatures on endurance and fatigue.

However, Fleming et al (1997) determined the effect of wearing a work glove on hand grip fatigue and compared the effect of sustained grip contraction of concentric versus eccentric nature. They also determined the physiological muscle performance and subjective perceptual fatigue during concentric and eccentric gripping. The authors recorded the (1) time to limit of endurance (T_{lim}); (2) rate of perceived effort (RPE); (3) mean power frequency (MPF) derived from the electromyogram (EMG); and (4) the fatigue objective-subjective relationship (FOSR, which is the correlation coefficient between RPE and MPF). They found that the T_{lim} was greater for no glove and eccentric muscle action. They determined that the FOSR was the greatest for the glove condition and isometric muscle action. The authors conclude that the glove condition and the type of handgrip contraction have an effect on the physiological fatigue and subjective perception of fatigue. With most tasks being performed at sub-maximal levels that are perceived by subjects, it is interesting to identify that the relation between perceived grasp force and the actual grasp force was linear for forces less than 80% MVC and piecewise quadratic for exertion that were more than 80%MVC on cylindrical handles (Cochran et al 2007).

This finding was consistent with the results from earlier researches (Bishu *et al.* 1994, Bronkema *et al.* 1994, Kim and Bishu 1997). These researches establish that people overexert initially to a peak level and then slowly reduce the grasp to a stable level in sub-maximal grasping. Three issues have been addressed in these researches including relationship between peak force and stable force, relationship between stable force and loads grasped, and grasp control during grasping. The researchers have identified the stable force to be the amount of variance of grasp force. The ratio of stable force to load lifted was found to be high at the low levels of loads and decrease as the load increased (Bronkema *et al.* 1994, Bishu *et al.* 1994). Similarly, grasp control was better at lower loads than at higher loads (Wilhelm and Bishu, 1997).

From the literatures discussed here the relation between static strength and endurance time is found to be non-linear and specific to the body part and task performed. Most literatures have evaluated such strength-endurance relations for power grasps with no available literature on endurance limit for precision gripping. Available literature on sub-maximal strength on precision gripping include that of Radwin and Oh (1992) who evaluated the finger forces in sub-maximal five finger static pinch task. They evaluated the finger forces at 10%, 20% and 30% of maximum voluntary exertions using two pinch spans. They observed that force contribution of the middle finger increased 25% to 38% when exertion level increased and the force contribution of the index finger decreased when load weight increased from 1 to 2 kg.

In summary knowledge of force exertions is important for biomechanical research, designing ergonomic tools and for process interventions as sustained excessive grip forces may accelerate musculoskeletal disorders. Literature survey identified limited information on sub-maximal performances and endurance time limits for precision gripping and the effect of gloves on such pinching tasks.

2.3 Prevalence of Musculoskeletal Disorder in Dental Profession

There are 173,900 dental hygienists and 294,020 dental assistants in the United States (BLS, 2009). The American Dental Hygiene Association defines a dental hygienist as a “licensed oral health professional who focuses on preventing and treating oral disease- both to protect teeth and gums, and also to protect patients’ total health” (ADHA, 2003). Dental practices are changing towards the use of dental hygienist to meet the patient load (Abbas 2004).

Epidemiological literature identifies that large number of these dental hygienists will experience musculoskeletal disorder during their carrier (Osbom et al 1990). Studies also show that MSDs in dental hygiene may cause limited ability to perform clinical dental hygiene as well as permanent chronic pain that may affect all aspects of life. There is a decline in the number of dental hygienists relative to the demand and trend towards an early retirement (BLS, 2009). Burke et al, (1997) did a retrospective analysis on 393 dentists with premature retirement because of illness between 1981 and 1992 in UK and found that premature retirements were due to musculoskeletal disorder (29.5%), cardiovascular disease (21%) and neurotic symptoms (16.5%). Occupationally related MSDs experienced by dental hygienists have recently received increased attention. According to study done by Oberg et al. (1990) the loss of income to dental practitioners due to MSD pain (lost work days) is greater than $41 million per year.

Recently, Lalumandier and McPhee (2001) surveyed 5,000 army dental professionals and identified that seventy five percent of the dental hygienist experienced hand problems of which fifty-six percent exhibited classic symptoms for carpal-tunnel syndrome. Similar results were reported by Macdonald et al 1988 and Liss et al 1995 using symptom survey or symptom in conjunction with vibrometry. The higher prevalence musculoskeletal disorder among the dental hygienist necessitates an evaluation of their tasks.

2.4 Dental hygiene task performance

Dental hygienists, assistants and students use a variety of both hand tools and powered tools including curets, ultrasonic scalers and motor driven hand pieces (Sanders and Turcotte 1997). These tools are of smaller diameter, cylindrical with thin angled tips at one or both ends that are used to remove the calculus and plaques and detect soft and hard tissue loss. The tools are firmly held within the compass of the fingers and manipulated (precision handling) that require forceful pinching.

Villanueva et al (2006) determined the relation between pinch force applied during periodontal scaling and the forces generated at the tip of the tool. They developed a biomechanical model to predict peak pinch forces and to calculate safety factor. The biomechanical model was evaluated by regressing tool tip forces with gravitational forces. They found that their biomechanical model moderately predicted pinch forces (with R^2=0.59) for experienced dentists and failed to predict pinch force for inexperienced dentists. They also found that students applied excessive forces during scaling.

This result of students applying excessive force during was supported by Dong et al (2006). In their study, Dong et al (2006) investigated the effect of periodontal instrument handle design on hand muscle load and pinch force. They evaluated ten custom designed dental scaling instruments of different diameters and weights with load cells and pressure sensors to perform a simulated scaling task. Evaluating the electromyogram recordings and pinch forces with subjective evaluations, they found that least amount of muscle load and pinch force was required for a 10mm diameter and 15grams instrument. The authors also established that the diameter of periodontal scaling tools should be of 10 mm as there was no effect on muscular load for diameters greater than 10 millimeters.

Similarly, Bramson et al (1998) evaluated of dental office risk factors and hazards through surveys and force measurements. They identified that the average pinch force exerted during periodontal scaling task was between 11% and 20% of the maximum pinch strength. They also reported that observation of the dental hygienist showed a 50% of their instrumentation was spent in scaling with an average maximum voluntary contraction of 14.48% for the scaling task.

2.5 Summary of the Literature

Review of the literature identified that different types of grasps are employed to perform daily tasks which require different levels of force exertion. Tasks are performed at sub-maximal levels of exertion which is affected by posture, grasp type, and gloves. These factors hinder force feedback which is critical for efficient muscular action leading to muscular fatigue. Literatures on muscular fatigue and the time to fatigue report contradictory results which mandate further investigation. The major limitation the literatures is the scarce information on muscular fatigue and endurance time at sub-maximal exertion levels for prehensile handling. Prehensile handling is commonly employed by dental hygienist at awkward postures when treating patients.

CHAPTER III

Research Rationale

3.1 Need for Research

A comprehensive literature search identified limited information about the relation between static strength and endurance time. Available information on endurance time has established that the relation between human force exertion and endurance is non-linear (Rohmert 1960, Garg et al 2002, and Manennica 1986). This information on non-linear endurance time is critical to engineers who design different tools for task performance. It is also necessary for the design engineers to understand the different factors that affect tool grasping.

Published literatures on grasps have determined that grasp strength is affected by posture, glove use and type of grasp employed. Most of these literatures have evaluated power grips where the tool is held within the compass of the entire hand. Limited information is available on the strength performances for precision handling (pinching) where the tools is held and manipulated within the compass of the fingers. Existing precision handling literatures have primarily evaluated three-jaw chuck pinch, pulp pinch, lateral or key pinch and finger press. However, dental professionals employ a modified pencil-hold grasp, where the tool is held and manipulated at the distal pads of the thumb, index and middle fingers, when attending to the patient’s needs.

Literature on the modified pencil-holds is limited with little information on the quantification of total forces exerted during dental tasks. United State Bureau of Labor Statistics (BLS) reports a decline in the number of available dental hygienists relative to the demand. This mismatch in the demand-supply of dental hygienists is because dental hygienists rank first among all occupations in the proportion of carpal tunnel syndrome per 1000 employee (Leigh and Miller 1998). The reason for the increased risk among the dental hygienists is that most of the periodontal tasks are performed at a perceived sub maximal level of exertion in awkward postures involving high pinch forces and vibration. Certain procedures are performed for a longer time period, as warranted by the patient's health conditions, with a sustained force exertion on the equipments. Therefore, it is reasonable to believe that the dental tasks are tiresome which involve forceful pinching, repetition and awkward postures that cause work-related musculoskeletal disorders (WMSDs).

A physically demanding dental task is also affected with the mandatory use of thin-gauge gloves to protect the professional from harmful pathogens that are present in the patient's body fluids. Current literatures on gloves have identified that critical sense of force exertion is affected leading to greater force exertion (Westling and Johansson, 1984, Bronkema et al 1994, Buhaman et al 2000, Wilhelm and Bishu 1997, and Shih et al 2001). This establishes the need to evaluate the precision grips as employed in dentistry.

In summary, force is an important risk factor and its sustainability is critical during task performance as it may lead to work related musculoskeletal disorders. From the literatures, endurance limits have been established for power grasps. However, there is no information on the endurance limits for precision grasps that is employed by dental professionals. Endurance limit information is important to establish accurate work-rest cycles as a possible ergonomic intervention for WMSDs. Precision grasps being an integral part of the dental tasks makes it a necessity to identify an endurance limit for a representative dental task.

3.2 Scope of this Dissertation

The current gap in literature on modified pencil-hold task and the risks associated with dental tasks motivates this dissertation to investigate the fundamental research question of how long can a dental professional exert and hold with pencil-hold before fatiguing. This research question will be answered in this dissertation by developing a force-endurance model. Knowledge about the forces required to perform dental tasks is crucial for the development of the model. For this reason, a representative dental hygiene task was identified and the required force to perform the task was established. Gloves are an integral part of any dental task and the amount of force exerted with it will be different from bare hand performance. Therefore it is reasonable to assume that the force-endurance relation for thin gauge glove will be different which establish the need for the development of a separate model for thin-gauge gloves. Similarly, the development of the relation warrants participants exert and endure forces at both maximal and different sub-maximal levels. People perceive exertion levels differently which necessitates the need to understand how forces are perceived during task performance. In this dissertation, the relation between the perceived and actual force exerted is also investigated as a separate objective. The following section lists the different objectives of this dissertation.

3.3 Objectives

Based on the need for this research, the modified pencil-hold is investigated with four specific objectives. The specific objectives of this dissertation are:

1. Force evaluations of a representative dental hygiene task,
2. Development of a force-endurance for modified pencil-hold grasp,

3. Development of a force-endurance relation for modified pencil-hold grasps using latex gloves and
4. Determination of a relation between expected and perceived force exertion levels.

3.4 Research Hypothesis

In this dissertation, three specific research hypotheses are evaluated that were developed from the research objectives. The research hypotheses that are evaluated include the following.

1. ***H_0:*** Dental hygiene scaling task require high levels of force exertions.

   Ha: Dental hygiene scaling task require low levels of force exertions

2. ***H_0:*** Forces exerted and the endurance time do not differ significantly for experts and novices for both bare hand and latex glove conditions.

   Ha: There is a significant difference in the force exertion and endurance time of experts and novices for both bare hand and latex conditions

3. ***H_0:*** The relation between the perceived and actual force exertion is linear.

   Ha: The relation between perceived and actual force exertions is non-linear

Hypothesis 1 was established to address the first research objective of evaluating the dental hygiene task. Hypothesis 2 was established to evaluate the second and third research objectives on force-endurance relation. Similarly, hypothesis 3 addresses the final objective of this dissertation on force perception.

CHAPTER IV

Research Methodology

In this chapter the methodological approach employed to answer the research question of how long can dental hygienists exert and hold using the pencil-hold before the onset of fatigue has been explained. Experimental rationale, procedure, and data analysis plan are the different sub-sections of this chapter that illustrate the research approach.

4.1. Rationale for Experiment

The primary motive of this dissertation is to develop a relation between the force exerted and the endurance time for precision handling. Real-time force and time data for both maximal and sub-maximal levels of exertions that are needed to develop such relations can be captured using force sensors. From the different force sensors (force sensing resistors (FSR), finger tactile pressure sensor (Finger TPS), and finger nail sensors) available, it is necessary to identify the most appropriate force-sensor and understand the logistics of wiring the sensors such that task performance is minimally hindered. In precision handling, the task is performed within the compass of the fingers. The forces exerted by each finger during task performance is expected to be different as published literatures have identified that different muscle groups control each finger performance which established the need to determine the finger-force exertion for a set of prehensile grasps. Accordingly, a preliminary study was designed to identify the force-capturing sensor and study the force exertion for three-jaw chuck and pencil-hold tasks.

Results from the preliminary study identified that Finger TPS is the suitable force sensor to be used for the development of force-endurance. Findings also determined that people exerted differently for different prehensile grasps.

From the preliminary study, it was decided that the force-endurance relation will be developed for modified pencil-hold as it is commonly employed by dental professionals. The dental professionals perform different tasks at varying sub-maximal levels of exertion that established the need to identify a representative dental task and determine its sub-maximal exertion level. For this reason, a separate experiment was designed to capture the sub-maximal exertion level for scaling task. This scaling exertion level was used to identify the limiting exertion level for the force-endurance curve. Similarly, gloves being an integral component of any dental task, it was decided to develop a separate force-endurance model for gloved hand condition. Simulating the real-time task performance, participants were required to perceive the different exertion levels during task performance. Limited information on the relation between perceived forces and actual forces motivated this research to develop a relation between perceived and actual forces for prehensile grasps.

The real-time force data collected in this research included three distinct phases: force build-up, sustained force and force fall-off. The sustained force exertions were captured using a data trimming procedures as explained in Section 4.3.1.

4.2. Research Methodology

This section details the procedures used both in the preliminary study and the actual main research. The preliminary study involved the determination of forces for chuck pinch and pencil-holds using force sensing resistors (FSRs). The main research involved two separate experiments. The first experiment included identification of a representative dental task and determination of its exertion level that was used to establish the limiting exertion level at 40%MVC for the second experiment. Force-endurance relations were developed and validated using real-time force data in the second experiment. In addition, real-time force data was also analyzed to establish a relation between perceived and actual forces.

4.2.1. Determination of Forces Exerted in Chuck-Pinch and Pencil-Holds

Force exertions for chuck pinch and pencil hold were determined using the support from a pilot research grant from National Occupational Research Area (NORA) of Heartland Center for Occupational Health and Safety. A copy of the complete report has been attached in the appendix (Appendix I). This experiment involved the development of a force-capturing methodology and the actual experiment of measuring the force exertions for chuck pinch and pencil-hold.

4.2.1.1. Development of Force-Capturing Methodology

Flexi Force® 0-25lb force sensing resistors (FSRs) backed with a data logger was used to capture the force exertions. Table 4.1 shows the specifications of the FSRs used in this part of the research.

Table 4.1 Specifications of Force Sensing Resistors

Thickness	0.008”
Length	7.75”
Width	0.55”
Sensing Area	0.375” Diameter
Linearity	±3%
Repeatability	±2.5%
Hysteresis	<4.5%
Drift	<5% logarithmic time scale
Response Time	<5μsec
Operating Temperature	15^0F-140^0F

Different calibration techniques (Subjective calibration, Universal testing machine (UTM), and Dead weights using a beam setup) were employed to simulate the actual test conditions. FSRs were calibrated using the dead weights with a beam setup as there were limitations in subjective calibration and with UTM. Figure 4.1 shows beam setup used for FSR calibration.

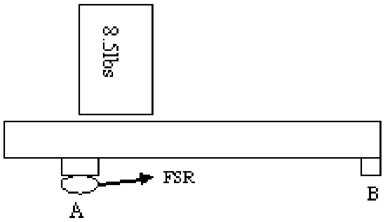

Figure 4.1 Beam Setup for FSR Calibration

The FSRs were calibrated for a range of 0-8.5lbs. Weights were applied in steps of 20 seconds between load applications. Regression analysis was performed to obtain the relation between applied force and measured force. A separate calibration equation was developed for each FSR.

Knowledge about the logistics of wiring the FSRs was important to record force exertions without any task hindrance. For this reason, a force capturing methodology was developed at a pilot level with two participants who exerted 2, 4, and 6 lbs on a B&L Engineering pinch gauge. In the force-capturing methodology, the FSRs were fixed at different locations as explained.

- *BARE:* FSRs were fixed to the distal phalanges of the thumb, and index finger of the subject
- *EBARE:* FSRs were fixed on the pinch gauge and bare hand pinch force was recorded.
- *GLOVEOUT:* Force exerted with the FSRs fixed over the vinyl glove at the distal phalanges of the thumb, and index finger
- *GLOVEIN:* Force exerted with FSRs fixed at the hand- vinyl glove interface of the distal phalanges of the thumb, and index finger
- *IN:* FSR reading at the hand-vinyl glove interface when the glove is sandwiched between 2 FSRs
- *OUT:* FSR reading at the vinyl glove-equipment interface when the glove is sandwiched between 2 FSRs

From the force recordings, it was decided to record forces for bare condition, and for gloved hand condition, force exertions within the glove and glove-equipment interface were measured as separate trials.

4.2.1.2. Force Exertions in Chuck Pinch and Pencil-Hold

A total of twenty participants (10 males and 10 females) performed a standard three-jaw chuck pinch and pencil hold for four hand conditions (bare hand, vinyl glove, latex glove, and nitryl gloves). The force-capturing methodology developed in Section 4.2.1.1., was used to record force exertions. For the pinch task, FSRs were fixed to the distal phalanges of the thumb, index and middle fingers. Participants were instructed to exert and hold 1, 3 and 5 lb on a B&L Engineering pinch gauge for 30 seconds with a minute break between trials to minimize finger fatigue. Each participant performed two repetition of each hand condition.

For the pencil hold task, FSRs were fixed to the distal phalanges of the thumb and index finger and at the third inter-phalangeal joint of the middle finger. Participants were instructed to exert and hold their maximum exertion to hold a pen for 5 seconds with one minute break between trials. Similar to the pinch task, forces were recorded for bare, vinyl, latex and nitryl gloved hand conditions. Each participant performed two repetition of each condition.

Results from the preliminary study (Appendix I) identified a significant glove effect with people overexerting more at lower load than higher loads for pinching task. It was also identified that force exertions were not uniform across fingers for both pinching and pencil-hold tasks.

4.2.1.3. Determination of Force Capturing Sensors

Results from pilot study also identified that force sensing resistors have limitations in capturing real time force exertions. An extensive literature search on force sensors identified that finger TPS system, using the capacitance principle, was suitable for this research. The finger TPS system consists of an orthogonally overlaying array of compressible dielectric electrodes that are separated by an air gap. Application of force reduces the air gap which increases the capacitance proportional to the force applied. Figure 4.2 shows the working principle of the finger TPS.

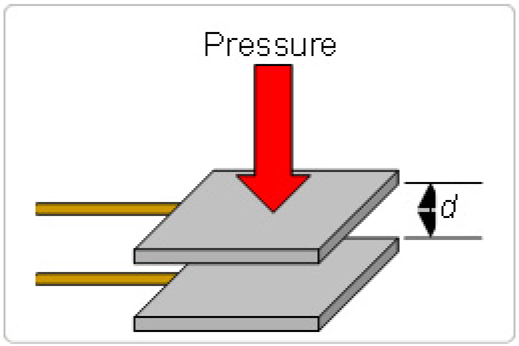

Figure 4.2 Working Principle of Finger TPS Sensors

The sensors are calibrated for every participant and for each test condition using a digital balance.   Table 4.2 shows the specifications of the finger TPS system.

Table 4.2 Specification of Finger TPS Sensors

Finger TPS Specification	
Thickness	2-3mm
Full Scale Range	10lbs
Sensitivity	0.1 lb
Temperature	0-500C
Repeatability	<4%FSR
Creep	2%
Scan Rate	60 Hz

4.2.2. Determination of Exertion Level for a Representative Dental Hygiene Task

Dental hygienists perform any or a combination of the following tasks (Abbas 2004): (1) taking dental and medical history, (2) performing intra-oral and extra-oral facial exams, (3) scaling, (4) root planning, (5) polishing, (6) exposing, processing and evaluating radiographs, (7) applying cavity preventing agents, and (8) counseling patients on oral hygiene techniques and good nutrition. These tasks require different levels of exertions to perform and identifying the force exertion level is critical to establish the minimum force level for force-endurance relation. Hand scaling was identified as the representative dental hygiene task because 31.7% of the appointment time involved hand scaling (Murphy, 1998).

4.2.2.1. Participants

Five dental hygienists (1 male and 4 females) participated in this experiment. Participants were practicing dental hygienists with at least three year of experience and are instructors at the College of Dentistry at University of Nebraska Medical Center. All the participants were right handed with an average age of 38 years.

4.2.2.2. Procedure

Before participating in the experiment the participants filled an informed consent form that was approved by the Institutional Review Board of University of Nebraska. Force and time data were captured using the Finger TPS sensors that were connected to a laptop through a data logger. The sensors were affixed to the distal phalanges of the thumb, index and middle fingers of the participants. Each of the five dental hygienists first performed maximal voluntary contraction (100% MVC) on a 204 S contra-angled, double ended scaler using the modified pencil-hold grasp. Maximum voluntary contraction was captured using a modified Caldwell regimen where the participants built the maximum force in the first seconds and sustained the force till they were unable to maintain the level. Participants performed the maximal exertion for bare hand condition and when they donned latex glove to simulate the actual working condition. Each participant performed two replications of the maximum exertion with a 15 minute break to recover from fatigue. A twenty-four hour break was provided before the participants performed the periodontal scaling task on a dental manikin as explained.

Periodontal Scaling Task: Five dental hygienists performed the oral prophylaxis scaling task with latex gloves. Each participant scaled a mandibular or a maxillary quadrant on all surfaces of each tooth in the quadrant using a dental manikin simulator with a 204 S contra-angled, double ended scaler (Hu-Friedy, Chicago, IL). Each tooth was prepared with artificial calculus and each participant was required to scale 2-3mm below the gingival to ensure the application of like scaling forces. Each tooth was scaled until the artificial calculus was completely removed.

4.2.2.3. Analysis Plan

Force and time data that were captured in this experiment were analyzed to identify the average exertion level for the periodontal scaling tasks. Data from the maximum voluntary contraction (MVC) was trimmed, using the data trimming logic to be explained in Section 4.3.1., to obtain the average sustained maximum force. Scaling force data being dynamic, the average scaling force was computed as the overall average force for all three fingers. Based on the average scaling force and average sustained maximum force, the exertion level for the scaling task was computed as the ratio between average scaling force and the average sustained maximal force. This sub-maximal exertion level was used to identify the limiting force level that is to be used in the development and validation of the force-endurance model.

4.2.3. Development of the Force-Endurance Model

The purpose of this experiment is to establish a relation between exertion level and endurance time for prehensile grasp. From the representative dental task force recordings, it was identified that the average exertion level for scaling task was 53.95%

of maximum voluntary contraction (MVC). To accommodate the 53.95 %MVC of scaling task within the force-endurance curve a limiting exertion level of 40%MVC was established. Similarly, the different force exertions levels that were evaluated include 100%, 90%, 80%, 60% and 40% of perceived exertion. Every participant performed all these exertion levels for both bare hand and latex gloved conditions.

4.2.3.1. Participants

A total of sixty participated in this experiment. The participants were recruited from University of Nebraska Medical Center (UNMC) and University of Nebraska-Lincoln (UNL). Participants from UNMC were students, who were juniors and seniors, and faculties from the dental hygiene program who had hands-on clinical experience. These participants were classified as experts who had experience in employing the modified pencil-hold grasp. Thirty experts (2 males and 28 females) with an average age of 25 participated in this part of the experiment. Participants from UNL were juniors, seniors and graduate students who were classified as novice as they had little to no experience of employing the modified pencil-hold grasp. Thirty novices (15 males and 15 females) with an average age of 24 performed this part of the experiment. All the participants self-declared healthy with no apparent neuromuscular disorder in the upper extremity.

4.2.3.2. Procedure

All the participants were explained about the importance of this research and were asked to sign an informed consent before participation. This experiment was performed for five days for each participant. In a day, the participant performed two repetitions for a given exertion level and for both bare hand and gloved hand conditions with a minimum of 20 minute break between trials. In this experiment, the participants were instructed to perceive the given level of exertion before exerting and holding the 204 S contra-angled, double ended scaler at that force level till exhaustion. Posture was standardized where the participant sat on chair and held the tool in their dominant hand such that the forearm was maintained parallel to the floor with no support for the arm. The order of exertion level and hand conditions was randomized to minimize the order effect. During the experiment, participant's thumb, index and middle fingers were wired with the Finger TPS system that was connected to a laptop computer through a data logger. The sensor captured real-time force exertions in pounds (lb).

4.3. Plan for Analysis

The collected data was first truncated to capture the sustained force using a data trimming procedure. The truncated data was then analyzed to identify significant factor effects. The primary objective of developing force-endurance models for modified pencil-holds was accomplished using linear and non-linear regression modeling techniques. Similarly, the relation between the perceived and actual forces was obtained using linear and non-linear regression techniques.

4.3.1. Data Trimming Procedure

A data trimming procedure was developed to eliminate noises in the data and to capture the sustained forces and their corresponding time-period. The procedure identified and corrected negative readings with zero as applied forces cannot be negative. Bins to develop force frequency were computed using standard deviations and number of force recordings (Scott 1979). A force frequency distribution was developed by sorting each recorded force into respective bin and the frequencies in each bin were computed. Sustained forces for maximal exertion were captured as the forces in bins that were within two standard deviation of the maximum bin value. Similarly, the sustained forces for sub-maximal exertions were determined as the force recordings in the bins that have the maximum frequency and bins that were ±2 standard deviations from the bin with maximum frequency. From the sustained force recordings, their corresponding time data was also computed. Section 5.3 shows a sample result of the data trimming procedure. The data trimming procedure also computed the average sustained forces for each finger and average time the sustained force was exerted for each test condition and saved in a separate Excel file. The entire data trimming procedure was coded and programmed in MATLAB using Microsoft Excel interface. Figure 4.3 shows the flowchart for data trimming of forces at maximal and sub-maximal levels.

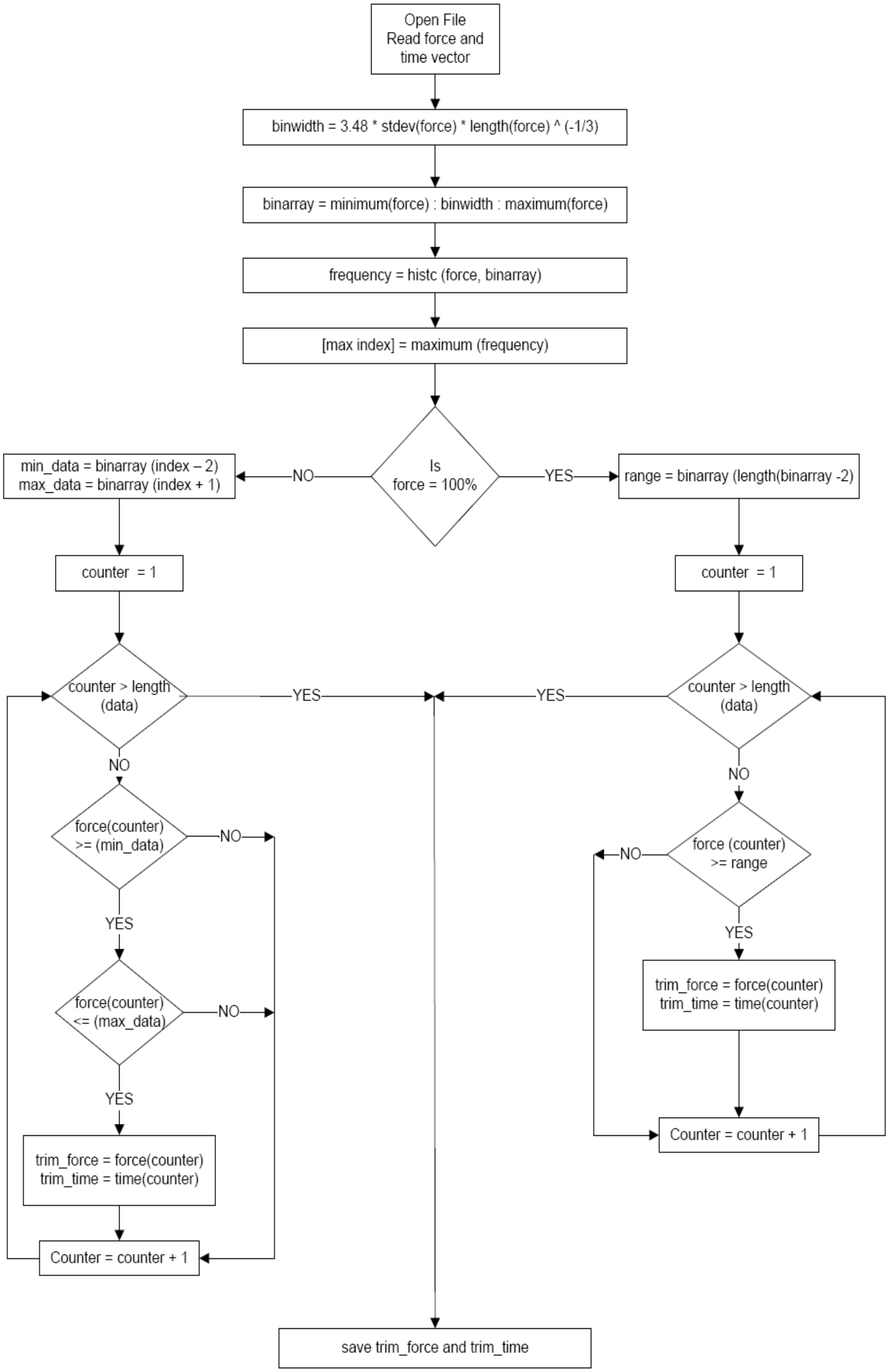

Figure 4.3 Data Trimming Logic

4.3.2. Determination of Factor Effects

Analysis of variance will be the primary analysis tool used to identify the effect of gloves, exertion level, subject, fingers and group. The dependent variables that will be evaluated in this analysis include force exerted and endurance time. The independent variables were hand conditions, exertion level, group, subject and their interactions with subjects being the random factor. The data will be analyzed using Proc Mixed in SAS.

$$Y_{ijklm} = \mu + H_i + L_j + Gr_k + + S(Gr)_{l(k)} + F_m + (Interactions) + \varepsilon_{ijklm}$$

Where

Y_{ijklm} = Endurance Time (sec) or Force Exerted (lb)

μ = Intercept

H_i = Hand Condition (Bare Hand, and Latex)

L_j = Level of Exertion (40%, 60%, 80%, 90% and 100%)

Gr_k = Group (Expert and Novice)

F_m = Effect of Fingers (Thumb, Index and Middle)

$S\ (Gr)_{l\ (k)}$ = Subject nested under group (60 subjects)

ε_{ijklm} = Error Component

4.3.3. Development and Validation of Force-Endurance Model

Regression modeling techniques will be used to establish a relation between endurance time and exertion level. The model development will involve both actual forces and theoretical forces where the actual forces are the forces that have been recorded during the tasking performance. The theoretical (desired) forces are the forces that will be computed as a percentage of maximum voluntary contraction (MVC). Exertion levels are computed as a ratio of the force over the respective MVC force recorded. Force and time data from 40 random subjects will be considered to develop the relation. The different models that will be developed include linear, logarithmic, exponential, quadratic, cubic and inverse equations. Table 4.3 shows the different models that are to be developed in this research. In all the developed models, the dependent variable (Y) will be endurance time and the independent variable (X) will be exertion level. The best fit model will be determined by comparing the Akaike's information criterion (AIC) values of each model. The model with the smallest AIC value is identified as the best-fit model.

Table 4.3 Regression Models

Model Functions	Regression Models
Linear	$Y= \beta_0+\beta_1 X$
Quadratic	$Y= \beta_0+\beta_1 X +\beta_2 X^2$
Cubic	$Y= \beta_0+\beta_1 X + \beta_2X^2 + \beta_3 X^3$
Inverse	$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$
Modified Inverse	$Y= \beta_0 +\beta_2 (1/X)$
Logarithmic Transformation	$Y= \beta_0+\beta_1*LN(X)$
Exponential Transformation	$Y= \beta_0+\beta_1*EXP(X)$

A significant glove effect is expected from previous researches (Wilhelm and Bishu, 1997, Bronkema et al 2000). For this reason separate regression models will be developed for both bare and gloved hand conditions using similar regression modeling techniques as shown in Table 4.3.

The models will be developed with normalized force data for both experts and novice using regression techniques. Normalization will involve the calculation of proportions from mean MVC force for each participant. The models developed will be validated using the force and time data from remaining set of 20 participants. The model validation procedure involves computation of predicted endurance times from the validation data using the identified best-fit regression model. A correlation analysis between the predicted endurance time and observed endurance time will be performed to establish the validity of the developed model.

4.3.4. Determination of the Relation between the Perceived Force and the Actual Force

With most tasks being performed at a sub-maximal level of exertion, it is important to identify how people perceive sub-maximal levels of force exertions. For this reason, a relation between the perceived force and actual force will be established. Regression modeling techniques will be employed to establish the relation between perceived and actual force. In this analysis, the dependent variable (Y) will be the perceived (actual) force proportion and the independent variable (X) will be the theoretical force proportion. The theoretical force will be computed as the percentage of the maximum voluntary contraction (MVC). The different regression models will be developed from the force data of 40 random subjects. The models that will be developed include linear, logarithmic, quadratic, cubic, exponential and inverse regressions as discussed in Section 4.3.3.

The best fit model will be identified by comparing the Akaike's information criterion (AIC) values of the different models. The perception of forces varies with individual and it is reasonable to identify any group effect on the perception forces. For this reason, separate regression models will be developed for both experts and novice using similar modeling techniques.

The models developed are validated using the force data from the remaining 20 participants. The model validation procedure will involve computation of predicted values for perceived forces from the validation dataset. A correlation analysis between the predicted and observed perceived forces will be performed to establish the validity of the developed models. A higher correlation coefficient between the predicted and observed values will establish that the models predict identical results.

CHAPTER V

Results

The findings from this research have been reported in this chapter. Results from the preliminary studies have been first discussed followed by the determination of exertion level for periodontal scaling task. The results from the variance analysis to identify the factor effects are then explained. In the end, results from the development of the different statistical models for the relation between endurance time and force exertion level and the relation between perceived and observed forces have been discussed.

5.1 Determination of forces exerted in Chuck-Pinch and Pencil-Holds

The force data captured using the FSRs for chuck-pinch and pencil holds were initially analyzed for factor effects using analysis of variance. The analysis was performed with recorded force as dependent variable for both chuck-pinch and pencil-hold. Hand conditions, fingers, force levels and subjects were the independent measures that were evaluated for the chuck pinch task. Similarly, the independent variables for the pencil-hold task included hand conditions, fingers and subjects. Table 5.1 summarizes the results obtained.

Table 5.1 ANOVA Summary for Chuck Pinch and Pencil-Hold

Factors	**Chuck pinch**	**Pencil-Hold**
Subject	*	*
Hand Condition	*	*
Finger	*	*
Force Level	*	NA
Subject x Hand Condition	*	*
Subject x Finger	*	*
Subject x Force level	*	NA
Hand Condition x Finger	*	*
Hand Condition x Force	*	NA
Finger x Force	*	NA

* - Significant at $\alpha = 0.05$ NA- Not evaluated

5.1.1. Force Analysis of Chuck-Pinch

Further analysis of the forces for chuck pinch identified significant differences in the force exerted at higher exertion levels for the different hand conditions. Figure 5.1 shows the force exertions for the different hand conditions.

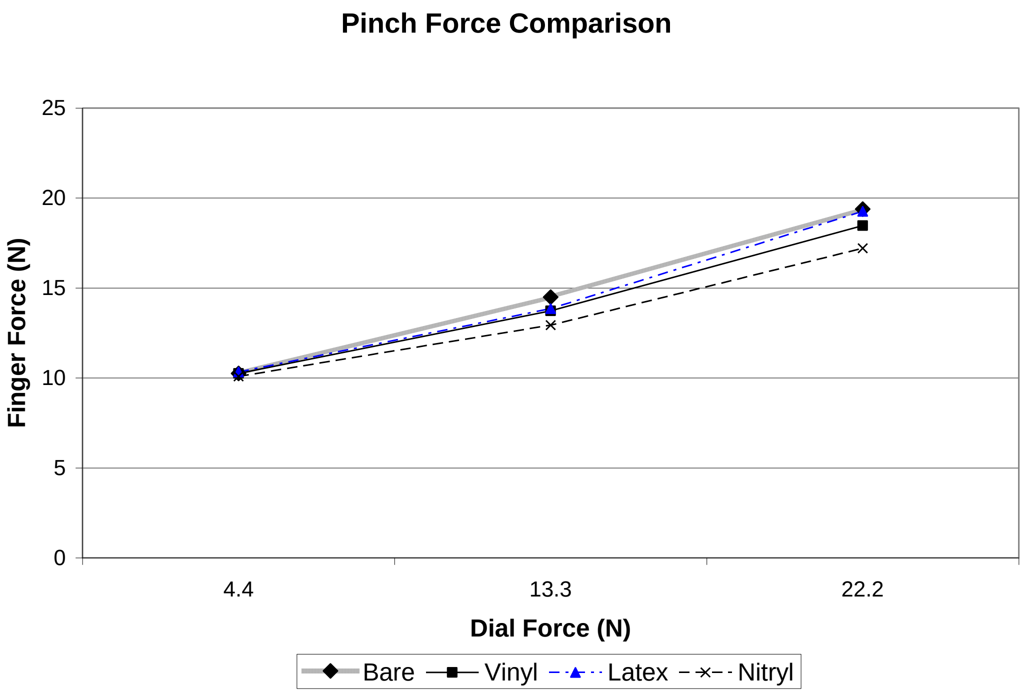

Figure 5.1 Force Exertions for Different Hand Conditions

From the above graph it is evident that force exertions with latex gloves were similar to the bare hand performance. However, force exertions were different with vinyl and nitryl gloves particularly at higher load levels. Evaluating the force ratio (ratio between force exerted and force needed) it was identified that participants exerted more force at lower levels and a stable force at higher levels (Figure 5.2). This result is consistent with the findings of Wilhelm and Bishu (1997).

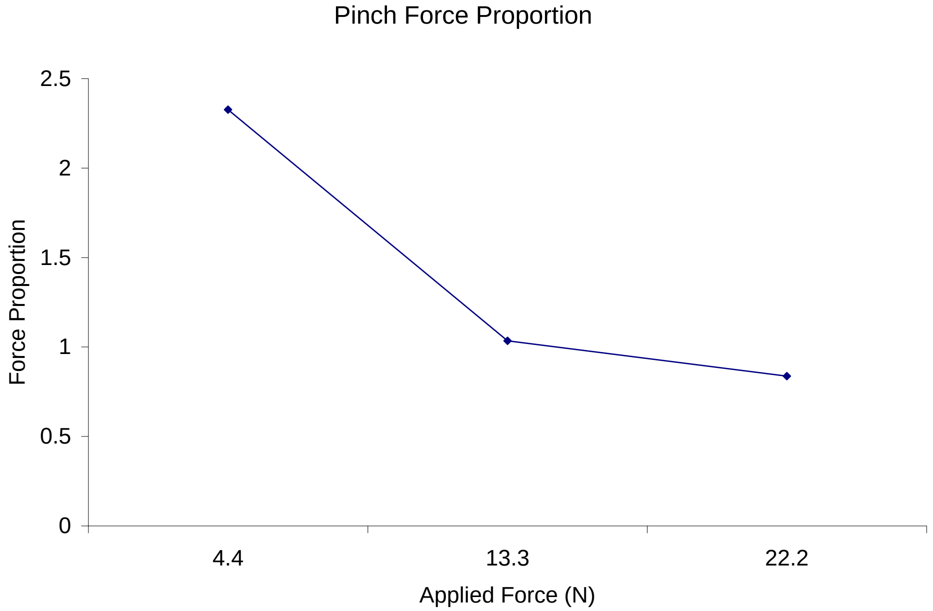

Figure 5.2 Force Ration for Sub-Maximal Exertion

Evaluation of the force exerted across thumb, index and middle fingers identified that maximum force was exerted with middle finger for all the hand conditions and force levels. Table 5.2 summarizes the average force exertions for each finger for different hand conditions and force levels.

Table 5.2 Average Finger Force Exertion

		Force (N)		
	Finger	**4.4**	**13.3**	**22.2**
Bare	**Thumb**	2.352	4.267	6.290
	Index	2.236	2.931	3.585
	Middle	5.666	7.293	9.512
Vinyl	**Thumb**	2.419	4.006	6.133
	Index	2.290	2.813	3.535
	Middle	5.542	6.913	8.802
Latex	**Thumb**	2.387	4.011	6.575
	Index	2.275	3.022	3.893
	Middle	5.674	6.819	8.794
Nitryl	**Thumb**	2.292	3.575	5.232
	Index	2.153	2.739	3.544
	Middle	5.643	6.621	8.434

In summary, results from chuck pinch force evaluations identified that people exert more force than what is needed. The extent of overexertion is more at lower levels than at higher level of load. Similarly, distribution of force exerted on fingers is not uniform with more force exerted by middle finger as compared to other two.

5.1.2. Force Analysis of Pencil-Hold

Similar to the force analysis of the chuck-pinch, the force evaluations identified a variation in the amount of force exerted for the different hand conditions. Figure 5.3 shows the force exerted to hold a pen for the different hand conditions.

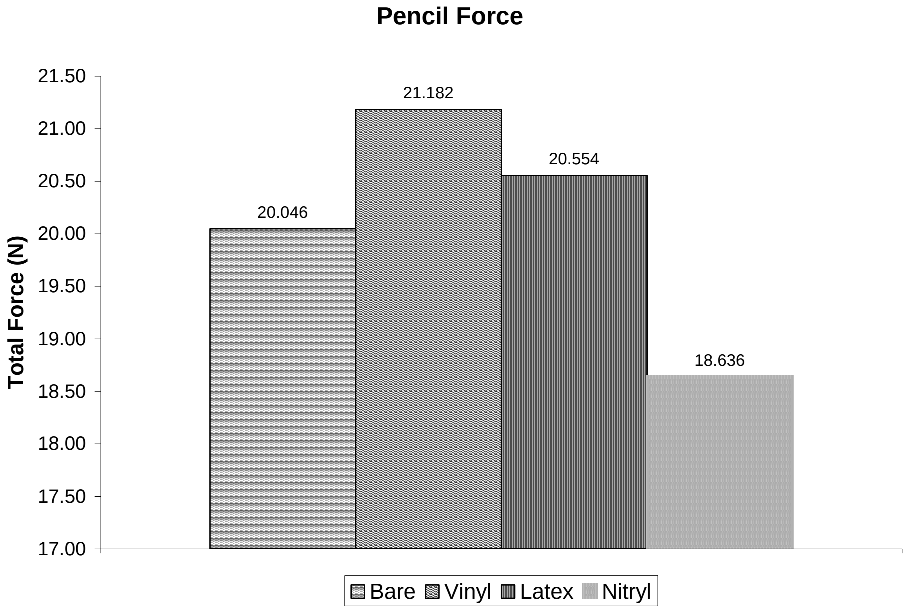

Figure 5.3 Pencil-Force Exertions for Different Hand Conditions

The variation in the average total force exerted as evidenced from the above figure establishes that people perceive force exertion differently with glove type. It is evident that people overestimate with nitryl gloves and underestimate with vinyl and latex gloves. The reason for such a variation may be due to material properties and thickness of gloves evaluated that may contribute to the tactile feedback critical for force exertions.

Evaluation of the finger force distribution for pencil holding task identified that maximum force was exerted with middle finger. Figure 5.4 shows the finger-force distribution for the pencil-hold task.

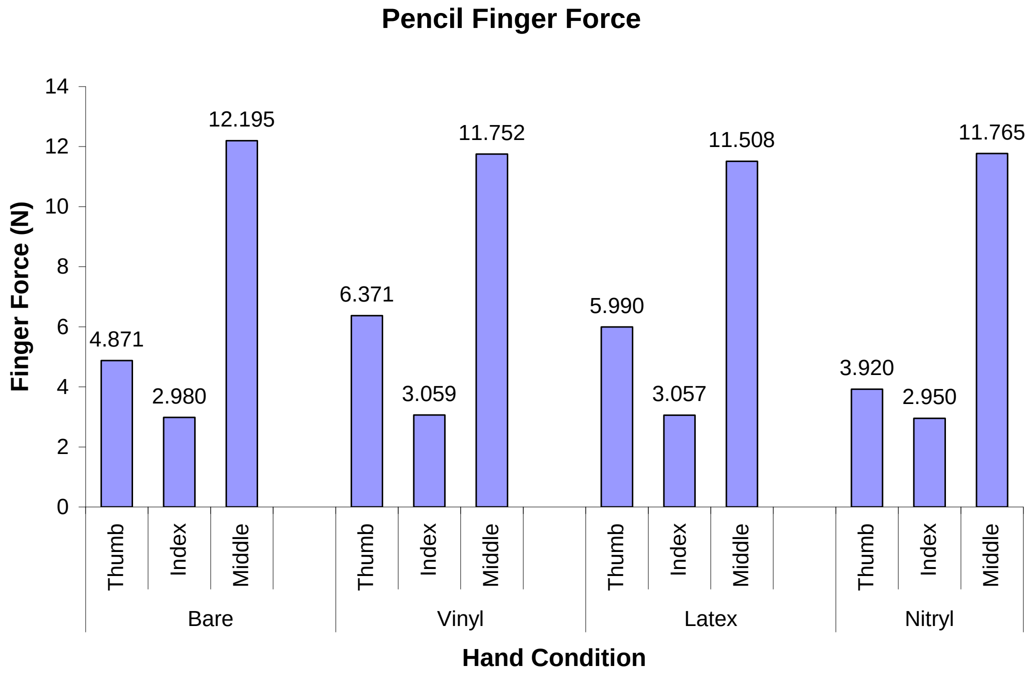

Figure 5.4 Pencil-Hold Finger Force Distribution

From the preliminary study, it can be concluded that people estimate force exertion differently with glove use. Maximum force recording with middle finger for both chuck-pinch and pencil-hold contradicts the previous finger force findings that maximum force is exerted with thumb. This contradiction indicates that force sensing resistors with a sensing area of Ø 0.375” is not suitable to capture force exertion with thumb warranting a different force sensor to capture finger force.

5.2. Identification of exertion level for periodontal scaling task

Results from the identification of scaling exertion level have been discussed in this section as this level was used to establish the limiting exertion level for the force endurance model. Sample data from the scaling task is shown in Figure 5.5.

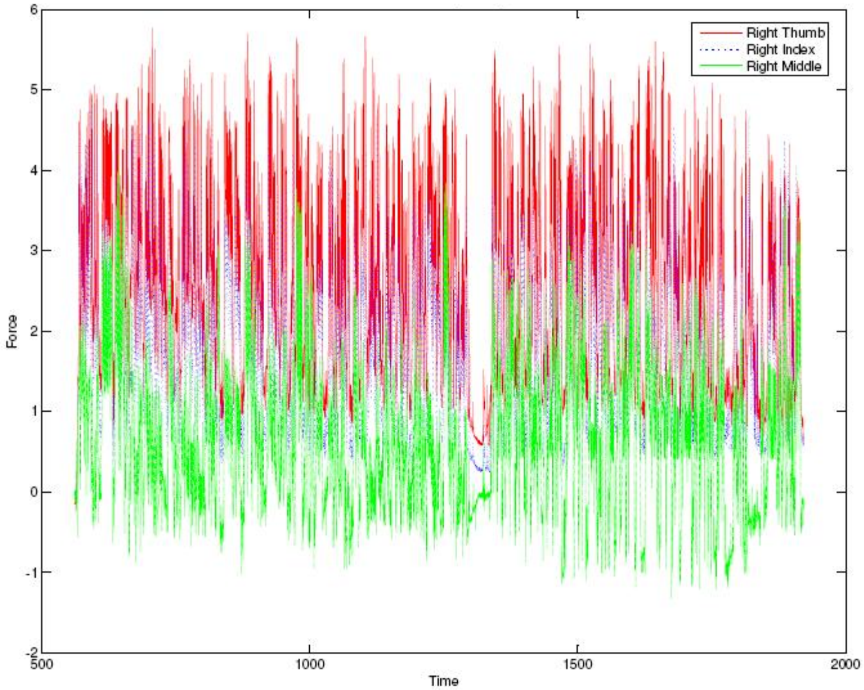

Figure 5.5 Force Recording from Periodontal Scaling Task

From the scaling task data the average scaling force was computed as the mean of the three finger forces. Table 5.3 shows the average scaling forces for each finger.

Table 5.3 Average Scaling Force

		Force (lb)		
Sub No	**Thumb**	**Index**	**Middle**	**Mean**
1	2.6111	1.8342	0.6236	*1.6896*
2	5.9614	3.6241	0.5111	*3.3655*
3	3.0883	1.8891	0.1188	*1.6987*
4	1.5366	0.6289	0.5158	*0.8937*
5	2.8497	1.8617	0.3712	*1.6941*
Mean	*3.2094*	*1.9676*	*0.4281*	***1.8684***

From the above table, it is evident that participants exerted with their thumb and index finger than the middle finger. Similarly, the average maximum forces of the five dental hygienists were also computed for thumb, index and middle fingers. Table 5.4 summarizes the average maximum forces for each finger.

Table 5.4 Average Maximum Force

	Force (lb)			
Sub No	**Thumb**	**Index**	**Middle**	**Mean**
1	3.5985	4.0796	3.1599	*3.6127*
2	5.0050	3.9352	1.3657	*3.4353*
3	5.0934	4.3682	3.5398	*4.3338*
4	6.2224	3.1682	3.0935	*4.1614*
5	2.7181	1.7139	0.8793	*1.7704*
Mean	*4.5275*	*3.4530*	*2.4077*	***3.4627***

The average exertion level for the scaling task was identified as the ratio between average scaling force and the average maximum force. Based on the average scaling level, the limiting level for the force-endurance model was established as 40% of the maximum level to accommodate the average scaling exertion of 53.95% within the endurance model.

$$Average\ Exertion\ Level = \frac{Average\ Scaling\ Force\ (lb)}{Average\ Maximum\ Force\ (lb)} = \frac{1.8684}{3.4627} = 0.5395$$

5.3 Data Trimming Procedure

The force and time data captures included noise that were eliminated using the data trimming logic as explained in Section 4.3.1 of Chapter 4. Figure 5.6 shows both the raw unedited data separately for each finger and the corresponding trimmed data.

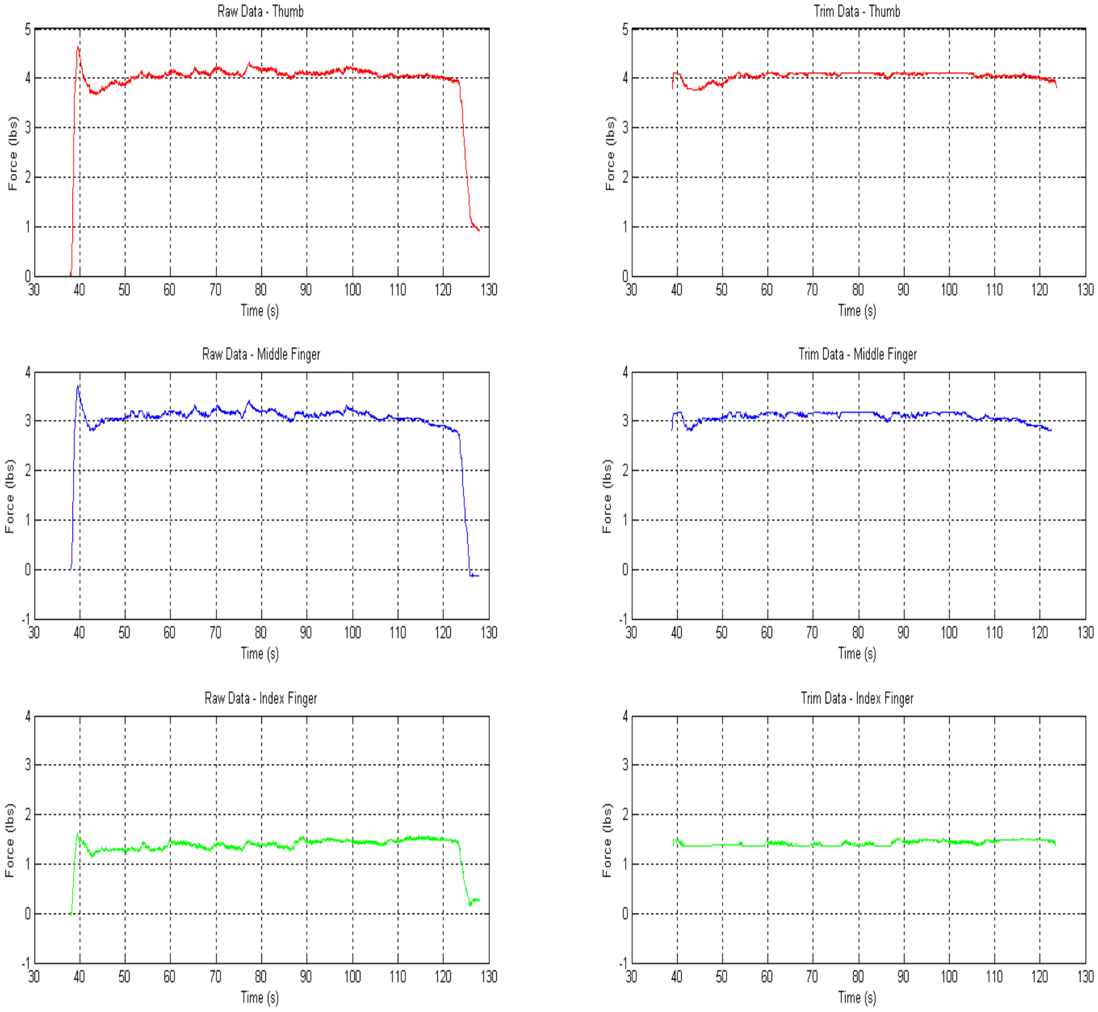

Figure 5.6 Raw and Trimmed Data Using the Logic

From the above figure, it is evident that the raw data includes a few seconds of force build-up which is followed by a period of stable force or sustained exertion and the last few seconds of force fall-off. For the analysis, only the stable force or sustained force recordings were required which was obtained using the trimming logic as explained in the previous chapter.

5.4 Evaluation of factor effects on Endurance time and finger force

In this section, results from analysis of variance (ANOVA) with endurance time as dependent variable are first discussed followed by the results from ANOVA with force exerted as dependent variable. Both the ANOVA model were performed at α = 0.05 to identify the factor effects on the force exerted and the endurance time. Table 5.5 summarizes the results from ANOVA.

Table 5.5 ANOVA Summary for Endurance Time and Force

	Endurance Time (sec)	**Force (lb)**
Hand	*	*
Level	*	*
Group	*	NS
Sub No (Group)	*	*
Finger	NS	*
Hand x Level	NS	NS
Hand x Group	NS	NS
Hand x Finger	NS	NS
Level x Group	*	NS
Level x Finger	NS	*
Group x Finger	NS	*
Hand x Group x Level	NS	NS
Hand x Level x Finger	NS	NS
Hand x GroupxFinger	NS	NS
Level x Group x Finger	NS	*

* Significant at α = 0.05 NS – not significant at α = 0.05

The ANOVA model developed for Endurance time is

$$Y_{ijkl} = \mu + H_i + L_j + G_k + S(G)_{l(k)} + (LxG)_{jk} + \varepsilon_{ijkl}$$

Where

Y_{ijkl} =

$Endurance\ Time\ for\ i^{th}\ hand\ condition, j^{th}\ exertion\ level, k^{th}\ group, and\ l^{th}\ subject$

$\mu = Intercept$

$H_i = Effect\ of\ i^{th} Hand\ condition\ (i = Bare, and\ Glove)$

$L_j = Effect\ of\ j^{th}\ Exertion\ Level\ (j = 40\%, 60\%, 80, 90\%, and\ 100\%)$

$G_k = Effect\ of\ k^{th} Group\ (k = Expert, and\ Novice)$

$S(G)_{l(k)} = Effect\ of\ l^{th}\ Subject\ nested\ under\ k^{th}\ Group\ (l = 1,2,3, \dots\dots, 20)$

$(LxG)_{jk} = Interaction\ Effect\ between\ j^{th} Exertion\ level\ and\ k^{th}\ group$

$\varepsilon_{ijkl} = Residual$

Similarly, the ANOVA model developed for Force exerted is

$$Y_{ijklm} = \mu + H_i + L_j + S(G)_{l(k)} + F_m + (L \times F)_{jm} + (G \times F)_{km} + (L \times G \times F)_{jkm} + \varepsilon_{ijklm}$$

Where

Y_{ijklm} =

$Force\ exerted\ for\ i^{th}\ hand\ condition, j^{th}\ exertion\ level, k^{th}\ group, l^{th}\ subject$
$and\ m^{th} finger$

$\mu = Intercept$

$H_i = Effect\ of\ i^{th} Hand\ condition\ (i = Bare, and\ Glove)$

$L_j = Effect\ of\ j^{th}\ Exertion\ Level\ (j = 40\%, 60\%, 80, 90\%, and\ 100\%)$

$G_k = Effect\ of\ k^{th} Group\ (k = Expert, and\ Novice)$

$S(G)_{l(k)} = Effect\ of\ l^{th}\ Subject\ nested\ under\ k^{th}\ Group\ (l = 1,2,3, \dots\dots, 20)$

$F_m = Effect\ of\ m^{th} Finger\ (m = Thumb, Index, and\ Middle)$

$(L \times F)_{jm} = \ Interaction\ Effect\ between\ j^{th}\ Exertion\ Level\ and\ m^{th}\ Finger$

$(G \times F)_{km} = Interaction\ Effect\ between\ k^{th}\ Group\ and\ m^{th}\ Finger$

$(L \times G \times F)_{jkm}$

$= \ Interaction\ Effect\ between\ j^{th}\ Exertion\ Level, k^{th}\ Group\ and\ m^{th}\ Finger$

$\varepsilon_{ijklm} = Residual$

5.4.1Discussion of Main and Interaction Effects for Endurance Time

Analysis of variance with endurance time as dependent variable revealed that all the main factors except fingers have a statistically significant effect on the endurance time. Evaluation of the interactions identified that only the interaction between exertion level and group had a significant effect on the endurance time. Section 5.4.1.1 – Section 5.4.1.5 discuss the effect of each contributing factor as listed in Table 3.

5.4.1.1Effect of Hand condition

Endurance Time was significantly affected by the hand condition with better performance for bare hand condition than gloved hand condition. Figure 5.7 shows the mean endurance times for both bare and gloved hand conditions.

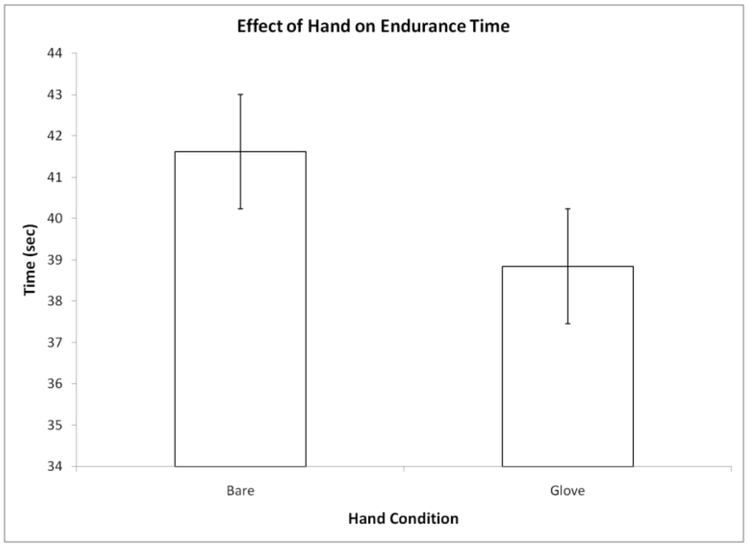

Figure 5.7Effect of Hand Condition on Endurance Time

From the above graph it is evident that people have 6.66% more endurance with bare hand condition than with latex glove.

5.4.1.2Effect of Exertion level

The different exertion levels had a significant effect on the endurance time as people exerted longer for low levels of exertion and for a shorter duration with higher level of exertion. Figure 5.8 shows the effect of exertion levels on endurance time.

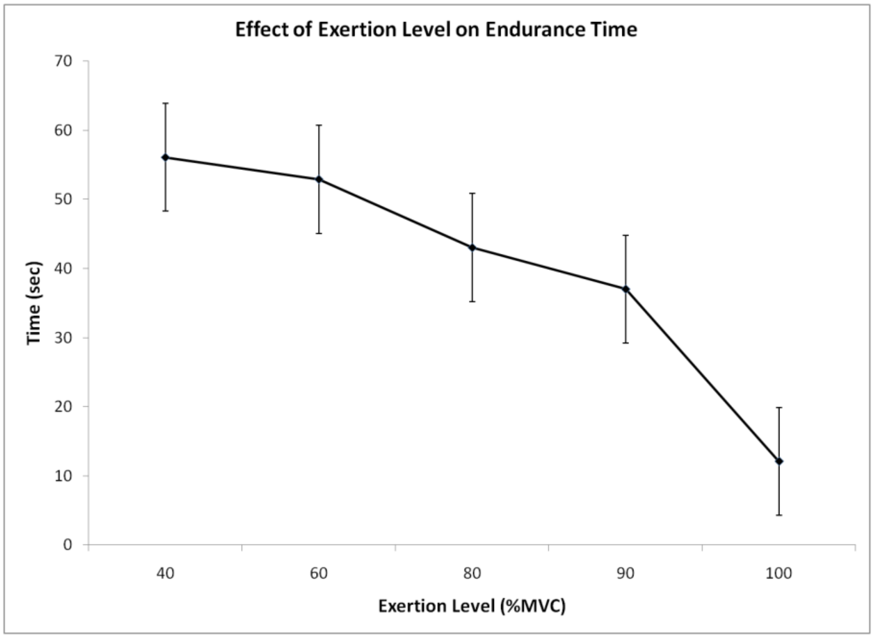

Figure 5.8 Effect of Exertion Level on Endurance Time

From the above graph it is evident that people endured longer at sub-maximal levels of exertion with 78.45% longer at40% MVC than 100%MVC.

5.4.1.3 Effect of Group

Group effect on endurance time identified that experts have more endurance than the novice group. This result was expected as the experts are trained to employ the modified pencil-hold during their clinical practice. Figure 5.9 shows the group effect on endurance time.

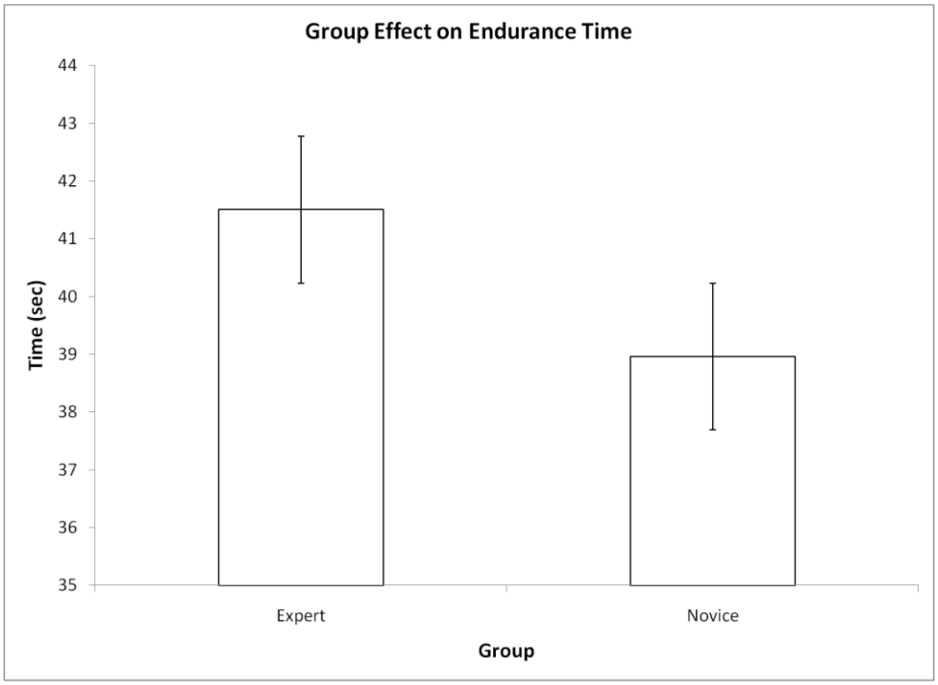

Figure 5.9 Effect of Group on Endurance Time

5.4.1.4 Interaction effect between Exertion Level and Group

The interaction between group and exertion level on endurance time is shown in figure 5.10. From the graph it is evident that the experts have better endurance than the novice as expected. The lack of training in exerting sub-maximal level of force was evident among the novices as evidenced at the 90% and 80% exertion levels.

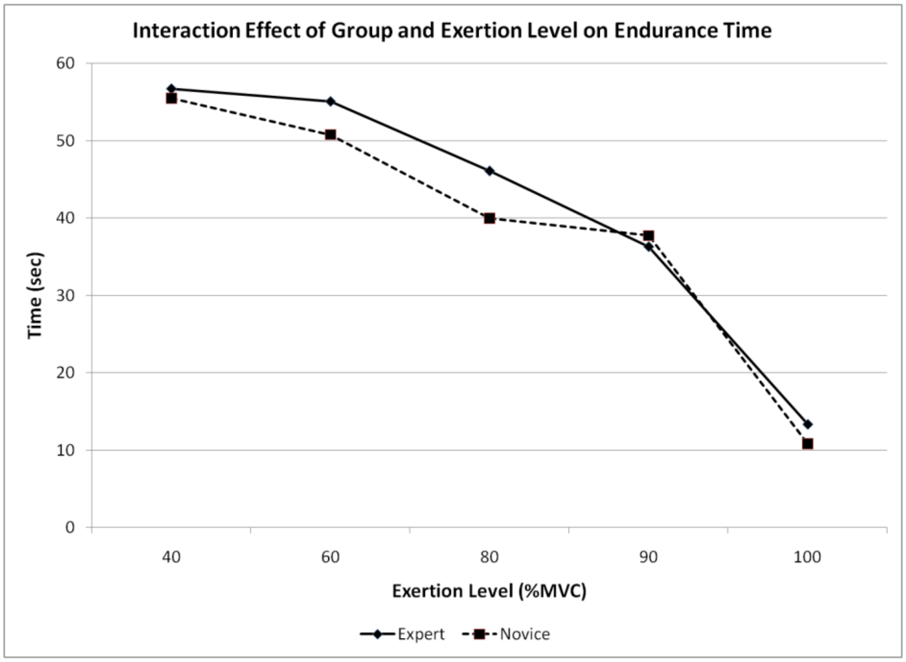

Figure 5.10 Interaction between Group and Exertion Level

5.4.1.5. Summary of factor effects on endurance time

Endurance time was significantly influenced by hand condition, exertion level, group and the interaction between group and exertion level. Results identified that participants have more endurance with bare hand condition and for lower level of exertions. Evaluations of the group effect identified that experts have more endurance than novice group which may be because of the training and practice to perform at sub-maximal exertion levels. The effect of training was evident in analyzing the interaction between the exertion level and group effect on endurance.

5.4.2Discussion of Main and Interaction Effects on Finger Force

Analysis of variance with dependent variable as finger force revealed that all the main factors except group had a significant effect on the finger force recorded at α = 0.05. Evaluation of the interactions identified that that the interactions between group, exertion level and finger affected the finger forces. Section 5.4.2.1 – Section 5.4.2.6 discuss the effects of variables on finger force.

5.4.2.1Effect of Hand Condition

Evaluation of hand conditions on the finger force revealed that people exerted more force with bare hand than gloved hand condition. This result establishes that gloves affect the perception of force exerted to grasp object which is consistent with earlier published literatures. Figure 5.11 shows the effect of hand condition on finger force.

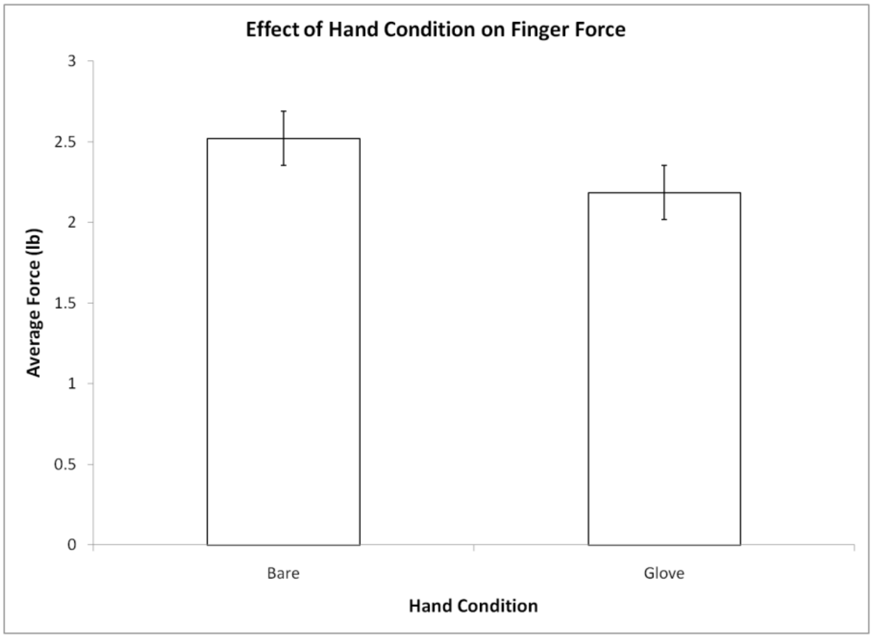

Figure 5.11 Effect of Hand Condition on Finger Force

From the above graph it is evident that people exert 13.35% more with latex gloves. This overexertion supports earlier findings that gloves hinder tactile feedback that is critical to force exertions.

5.4.2.2 Effect of Exertion Level

Figure 5.12 shows the average force exerted for different exertion levels. From the graph it is evident that people underestimate force exertion by 30.52% on an average for the sub-maximal levels of exertion.

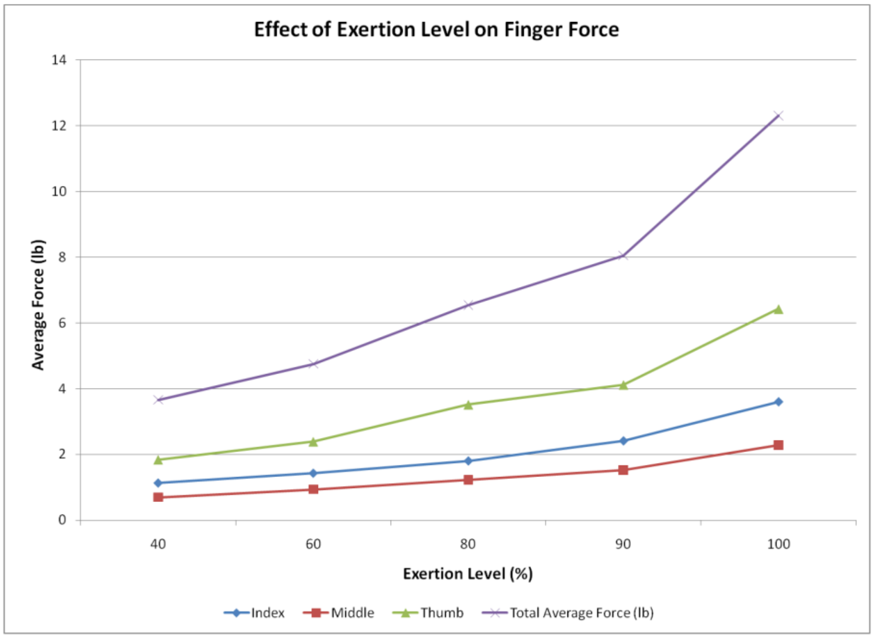

Figure 5.12 Effect of Exertion Level on Finger Force

This result establishes the need to estimate the perception of sub-maximal level of exertion which will assist in the redesign of tools and work schedules.

5.4.2.3. Effect of Fingers

Force exertion pattern during the modified pencil-hold task was identified in analyzing the effect of fingers on force exertion. Figure 5.13 shows the effect of finger on force exertion.

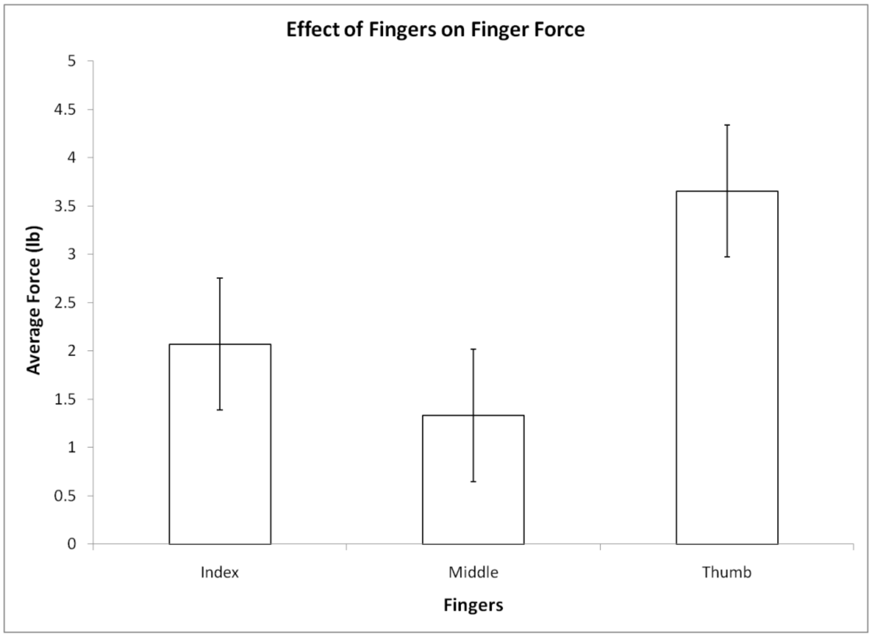

Figure 5.13 Effect of Fingers on Force Exertion

From the above graph it is evident that in the modified pencil-hold grasp, maximum force is exerted by the thumb (~51.79%) followed by index (~29.34%) and middle (~18.88%). Lesser force on the middle finger identifies its role of supporting the tool during task performance.

5.4.2.4. Effect between level and finger

Force exertion pattern was similar to the overall force exertion pattern with maximum force being exerted by the thumb followed by index and middle fingers. Figure 5.14 shows the interaction between exertion level and finger.

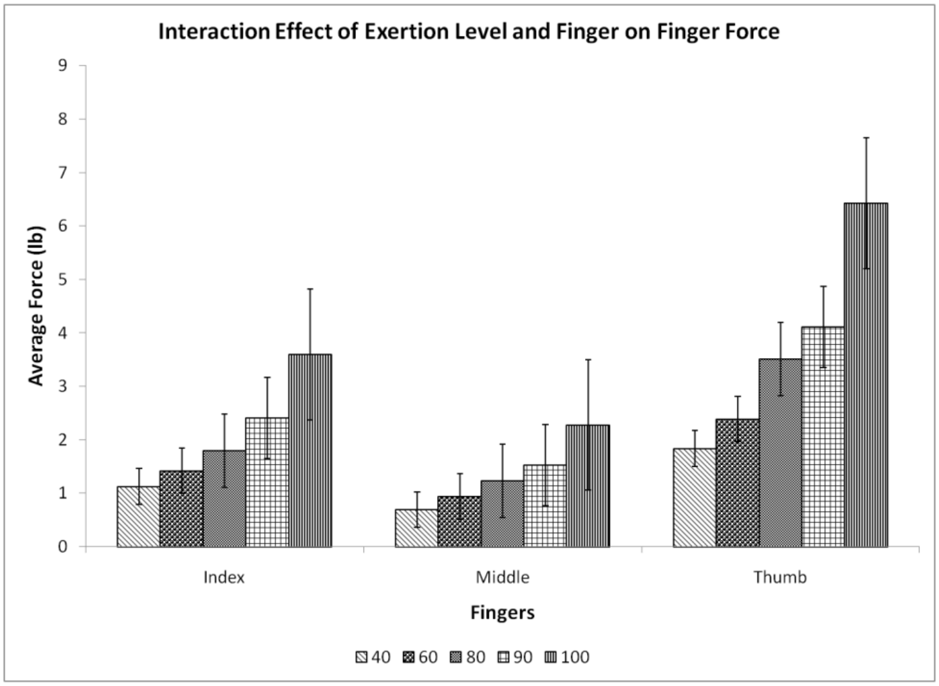

Figure 5.14 Interaction between Finger and Exertion Level on Finger Force

5.4.2.5. Effect of Group and Finger

Interaction between the group and fingers identified similar exertion patterns for both experts and novices. However, the novice group was identified to exert more force with their thumb than the experts. The expert group was found to exert more with the index and middle fingers than the novice. Figure 5.15 shows the interaction between group and finger on force exerted.

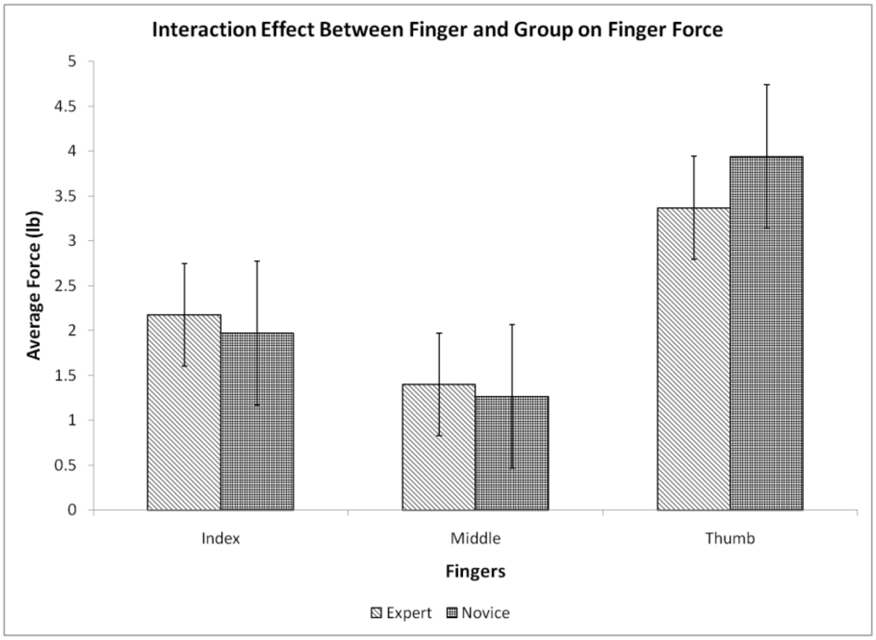

Figure 5.15 Interaction between Group and Finger on Exertion

5.4.2.6. Summary of factor effects on finger force:

Results identified that participants exerted more force with bare hand than gloved hand condition which is consistent with published evidences on glove hindrance over performance. Other findings in this research is that novice exerted more force than the experts. Evaluations of the finger force distribution identified that maximum force was exerted by thumb, followed by index and middle fingers in order.

5.5. Force-Endurance Models

5.5.1. Development of Force-Endurance Models

Different regression modeling techniques were employed to establish a relation between endurance time (ET) and the force exerted (%MVC). For this analysis, the force and time data from forty random subjects were used to establish the relation. Modeling involved endurance time as the dependent variable (Y) and force proportions (X) as the independent variable. Separate models were developed for actual force proportions and theoretical force proportions. Similarly, distinct regression models for experts and novice groups both for bare hand and glove condition were developed because endurance time and force exertion varied with group and hand conditions as evidenced in Section 5.4. Models were compared using AIC values to identify the best fit model.

Modeling with force proportions as independent variables included actual force proportions, theoretical force proportions, mean actual proportions, mean theoretical proportions, overall actual proportions and overall theoretical proportions. The actual force proportions were computed as the ratio between the actual forces and the average maximum voluntary contraction (MVC) force for each participant. The theoretical force proportion was calculated as the ratio between the percentage of MVC force for each level of exertion and the maximum voluntary contraction force for each participant. The mean actual force proportion was computed as the average actual force proportion between trials for each participant. Similarly, the mean theoretical force proportion was computed as the average theoretical force proportions between trials for each participant. The overall force proportions were computed as the average proportions for each level of exertion that was evaluated in this research. Tables 5.6 and 5.7 summarize the AIC values of models with expert data for bare hand and gloved hand conditions respectively.

Table 5.6 AIC Values from Regression for Experts with Bare Hand

	R-square					
	Actual Force Proportion	Theoretical Force Proportion	Mean Actual Force Proportion	Mean Theoretical Force Proportion	Overall Actual Force Proportion	Overall Theoretical Force Proportion
$Y= \beta_0+\beta_1 X$	1280.045	1250.260	741.383	735.994	15.988	26.236
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	1281.833	**1236.858**	743.144	**734.419**	15.867	15.619
$Y= \beta_0+\beta_1 X + \beta_2 X^2 + \beta_3 X^3$	**1275.152**	1238.117	744.900	735.795	**11.951**	**8.965**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	1279.749	1238.766	742.454	735.145	13.863	20.544
$Y= \beta_0 +\beta_2 (1/X)$	1291.304	1264.198	742.092	739.986	26.018	29.107
$Y= \beta_0+\beta_1 LN(X)$	1284.674	1257.253	**740.857**	737.959	21.963	27.877
$Y= \beta_0+\beta_1 EXP(X)$	1280.771	1245.843	742.117	734.773	14.109	24.811

Table 5.7 AIC Values from Regression for Experts with Gloved Hand

	AIC Values					
	Actual Force Proportion	Theoretical Force Proportion	Mean Actual Force Proportion	Mean Theoretical Force Proportion	Overall Actual Force Proportion	Overall Theoretical Force Proportion
$Y= \beta_0+\beta_1 X$	1239.273	1239.791	642.288	641.517	12.099	24.359
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	1239.978	1225.204	643.171	636.582	-3.124	20.041
$Y= \beta_0+\beta_1 X + \beta_2 X^2 + \beta_3 X^3$	1241.833	**1218.803**	**638.580**	**635.857**	**-12.604**	**5.628**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	1240.831	1230.411	643.328	638.541	6.136	22.709
$Y= \beta_0 +\beta_2 (1/X)$	1262.692	1253.012	647.147	648.407	24.784	27.181
$Y= \beta_0+\beta_1 LN(X)$	1247.673	1246.583	644.218	644.976	20.561	25.949
$Y= \beta_0+\beta_1 EXP(X)$	**1238.103**	1235.030	641.174	639.227	-0.806	22.977

From the above tables, it is evident that force-endurance relation for experts mostly followed a second-order or third-order polynomial function for most conditions. The relation for experts with gloved hand condition was found to follow a third order polynomial function for actual and theoretical force proportions. Regression models with theoretical force proportions were found to have low AIC values which indicate that theoretical force proportions were better predictors of endurance time as expected.

Similarly, regression results with novice dataset have been summarized in Tables 5.8 and 5.9 for bare hand and gloved hand conditions respectively. From the results, it is evident that the relations for novice dataset also follow a third-order polynomial fit. Findings from this research support previous research on endurance time (Rohmert 1960).

Tables 5.10 and 5.11 summarize the different relations between exertion level and endurance time for a simulated dental task. The models that have been presented are true to the test conditions evaluated in this research.

Table 5.8 AIC Values from Regression for Novice with Bare Hand

	AIC Values					
	Actual Force Proportion	Theoretical Force Proportion	Mean Actual Force Proportion	Mean Theoretical Force Proportion	Overall Actual Force Proportion	Overall Theoretical Force Proportion
$Y= \beta_0+\beta_1 X$	1273.938	1245.812	637.463	624.421	15.471	26.592
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	1269.748	1223.250	637.130	**613.267**	13.323	22.069
$Y= \beta_0+\beta_1 X + \beta_2 X^2 + \beta_3 X^3$	**1263.239**	**1221.674**	**633.184**	614.161	15.181	**21.762**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	1275.785	1227.759	639.452	615.239	12.729	23.961
$Y= \beta_0 +\beta_2 (1/X)$	1281.93	1265.271	644.233	635.391	25.421	29.086
$Y= \beta_0+\beta_1 LN(X)$	1273.364	1255.751	638.285	630.009	21.595	27.991
$Y= \beta_0+\beta_1 EXP(X)$	1281.688	1239.186	641.436	620.764	**11.816**	25.435

Table 5.9 AIC Values from Regression for Novice with Gloved Hand

	AIC Values					
	Actual Force Proportion	Theoretical Force Proportion	Mean Actual Force Proportion	Mean Theoretical Force Proportion	Overall Actual Force Proportion	Overall Theoretical Force Proportion
$Y= \beta_0+\beta_1 X$	1224.829	1196.365	594.517	577.836	15.539	24.640
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	1226.775	1185.459	596.501	572.277	16.887	23.802
$Y= \beta_0+\beta_1 X + \beta_2 X^2 + \beta_3 X^3$	**1220.791**	**1174.261**	**592.175**	**567.942**	**5.186**	**18.775**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	1223.612	1190.547	594.357	575.063	17.446	25.115
$Y= \beta_0 +\beta_2 (1/X)$	1257.125	1213.600	613.750	588.638	23.462	27.023
$Y= \beta_0+\beta_1 LN(X)$	1235.342	1204.828	600.886	583.117	19.770	25.928
$Y= \beta_0+\beta_1 EXP(X)$	1227.956	1190.806	596.209	574.458	14.891	23.599

Table 5.10 Force-Endurance Models for Experts

	Expert with Bare Hand	**Expert with Glove Hand**
Actual Force Proportion	$ET=26.496+140.202(\%MVC)-247.226(\%MVC)^2+104.995(\%MVC)^3$	$ET=76.769-20.005exp(\%MVC)$
Theoretical Force Proportion	$ET=-1.441+214.653(\%MVC)-197.846(\%MVC)^2$	$ET=235.096-931.340(\%MVC)+1513.620(\%MVC)^2-804.669(\%MVC)^3$
Mean Actual Force Proportion	$ET=30.400-22.253LN(\%MVC)$	$ET= 102.602-353.252(\%MVC)+691.14(\%MVC)^2-424.289(\%MVC)^3$
Mean Theoretical Force Proportion	$ET= 10.737+215.914(\%MVC)-210.106(\%MVC)^2$	$ET=212.265-791.753(\%MVC)+1289.008(\%MVC)^2-696.690(\%MVC)^3$
Overall Actual Force Proportion	$ET=6.195+356.098(\%MVC)-694.639(\%MVC)^2+345.311(\%MVC)^3$	$ET=70.571-58.792(\%MVC)+46.133(\%MVC)^2-45.462(\%MVC)^3$
Overall Theoretical Force Proportion	$ET=110.067-314.266(\%MVC)+637.041(\%MVC)^2-419.388(\%MVC)^3$	$ET=212.860-794.716(\%MVC)+1393.589(\%MVC)^2-698.893(\%MVC)^3$

ET - Endurance Time

%MVC – Force proportions calculated from maximum voluntary contraction

Table 5.11 Force-Endurance Model for Novice

	Novice with Bare Hand	**Novice with Glove Hand**
Actual Force Proportion	$ET=45.483+79.793(\%MVC)-191.829(\%MVC)^2+89.492(\%MVC)^3$	$ET=41.314+92.570(\%MVC)-217.595(\%MVC)^2+103.632(\%MVC)^3$
Theoretical Force Proportion	$ET=146.007-494.585(\%MVC)+892.761(\%MVC)^2-532.478(\%MVC)^3$	$ET=285.293-1115.970(\%MVC)+1713.181(\%MVC)^2-889.035(\%MVC)^3$
Mean Actual Force Proportion	$ET=41.226+108.245(\%MVC)-242.657(\%MVC)^2+113.982(\%MVC)^3$	$ET=39.532+108.781(\%MVC)-254.274(\%MVC)^2+125.648(\%MVC)^3$
Mean Theoretical Force Proportion	$ET=-6.495+243.942(\%MVC)-223.998(\%MVC)^2$	$ET=257.828-979.223(\%MVC)+1519.738(\%MVC)^2-787.307(\%MVC)^3$
Overall Actual Force Proportion	$ET= 107.796-35.832\exp(\%MVC)$	$ET=160.329-603.896(\%MVC)+1001.341(\%MVC)^2-547.695(\%MVC)^3$
Overall Theoretical Force Proportion	$ET=148.643-505.152(\%MVC)+904.679(\%MVC)^2-536.321(\%MVC)^3$	$ET=288.666-1132.762(\%MVC)+1757.144(\%MVC)^2-901.523(\%MVC)^3$

ET - Endurance Time

%MVC – Force proportions calculated from maximum voluntary contraction

5.5.2. Validation of the relation between Force and Endurance

This section summarizes the validation results for the force-endurance models that were developed in section 5.5.1 using the force data from a different set of 20 subjects. The models were validated by computing the Pearson's correlation coefficient between the predicted endurance time values and the observed endurance time values for each test condition. Table 5.12 summarizes the correlation coefficients for each test condition.

Table 5.12 Pearson's Correlation Coefficients for Validated Data

	Actual Force Proportion	Theoretical Force Proportion	Mean Actual Force Proportion	Mean Theoretical Force Proportion	Overall Actual Force Proportion	Overall Theoretical Force Proportion
Expert with Bare Hand	0.4231	0.5247	0.4138	0.5489	0.9750	0.9891
Expert with Glove Hand	0.5136	0.5555	0.5549	0.5783	0.9743	0.9933
Novice with Bare Hand	0.4756	0.6011	0.5351	0.6600	0.9654	0.9499
Novice with Glove Hand	0.5658	0.6976	0.6680	0.7509	0.9840	0.9873

From the above table, it is interesting to identify that the regression models for novice predicted better than the models for experts. Similarly, modeling with theoretical force proportions has better correlation than models with actual force proportions.

5.6. Determination of Relation between Actual and Perceived Forces

5.6.1. Development of the Relation between Actual and Perceived Forces

People perceive and exert differently at various levels which necessitates an understanding between the perceived level of exertion and the actual force exerted to enhance work schedules and tool design. Different regression modeling techniques were used to establish the relation between actual and perceived forces. Force proportions were used in this analysis with actual force proportions and theoretical force proportions as the dependent measure and independent variable respectively. Modeling of actual and perceived forces included true force proportions, mean force proportions and overall force proportions. Mean force proportions are the average force proportions between trials for each participant. Similarly, overall force proportions are the average force proportions for each level of exertion evaluated in this research. Separate regression models were developed for expert and novice with independent models for bare hand and gloved hand. The best fit models were identified using AIC values. Table 5.13 – Table 5.16 summarize the AIC values for the different models that were evaluated in this research.

Table 5.13 Relation between Perceived and Actual Force for Experts with Bare Hand

	AIC Values		
	True Force Proportions	Mean Force Proportions	Overall Force Proportions
$Y= \beta_0+\beta_1 X$	-575.305	-303.77	-18.8866
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	-599.077	-316.38	-22.8613
$Y= \beta_0+\beta_1 X + \beta_2 X^2 + \beta_3 X^3$	**<u>-605.928</u>**	**<u>-320.897</u>**	**<u>-39.2141</u>**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	-592.081	-311.989	-20.3136
$Y= \beta_0 +\beta_2 (1/X)$	-540.789	-284.556	-15.5489
$Y= \beta_0+\beta_1 LN(X)$	-558.218	-294.194	-17.0063
$Y= \beta_0+\beta_1 EXP(X)$	-586.029	-309.904	-20.5302

From the above table it is evident that the relation between the perceived force and the actual force level for experts with bare hand followed cubic function.

Table 5.14 Relation between Perceived and Actual Force for Experts with Gloved Hand

	AIC Values		
	True Force Proportions	Mean Force Proportions	Overall Force Proportions
$Y= \beta_0+\beta_1 X$	-624.241	-330.159	-19.910
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	-656.626	-346.847	-24.918
$Y= \beta_0+\beta_1 X + \beta_2 X^2 + \beta_3 X^3$	**-665.008**	**-352.531**	**-50.430**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	-647.673	-341.385	-21.952
$Y= \beta_0 +\beta_2 (1/X)$	-578.159	-304.206	-15.846
$Y= \beta_0+\beta_1 LN(X)$	-601.199	-317.158	-17.591
$Y= \beta_0+\beta_1 EXP(X)$	-638.812	-338.449	-21.991

Similar to the results for experts with bare hand, the relation between the perceived force and the actual force level for experts with gloved hand was also found to follow a cubic function.

Table 5.15 Relation between Perceived and Actual Force for Novice with Bare Hand

	AIC Values		
	True Force Proportions	Mean Force Proportions	Overall Force Proportions
$Y= \beta_0+\beta_1 X$	-499.152	-267.177	-19.041
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	-513.101	-274.921	-23.792
$Y= \beta_0+\beta_1 X + \beta_2 X^2 + \beta_3 X^3$	**-513.618**	**-274.956**	**-28.317**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	-509.918	-272.803	-21.284
$Y= \beta_0 +\beta_2 (1/X)$	-477.713	-254.952	-15.504
$Y= \beta_0+\beta_1 LN(X)$	-488.696	-261.147	-17.039
$Y= \beta_0+\beta_1 EXP(X)$	-505.44	-270.911	-20.777

From the above table, the relation between perceived force and actual force level for novice with bare hand condition was found to be a cubic function.

Table 5.16 Relation between Perceived and Actual Force for Novice with Glove Hand

	AIC Values		
	True Force Proportions	Mean Force Proportions	Overall Force Proportions
$Y= \beta_0+\beta_1 X$	-532.481	-275.413	-17.801
$Y= \beta_0+\beta_1 X +\beta_2 X^2$	-559.333	-289.864	-24.3468
$Y= \beta_0+\beta_1 X + \beta_2X^2 + \beta_3 X^3$	**-561.954**	**-290.323**	**-29.5573**
$Y= \beta_0+\beta_1 X +\beta_2 (1/X)$	-553.363	-286.523	-21.1413
$Y= \beta_0 +\beta_2 (1/X)$	-501.595	-257.931	-14.3753
$Y= \beta_0+\beta_1 LN(X)$	-516.934	-266.578	-15.8497
$Y= \beta_0+\beta_1 EXP(X)$	-542.439	-281.092	-19.5132

The relation between the perceived force and actual force level for novice was found to follow cubic function from Table 5.17. The different regression models that were developed between actual force exertions and perceived force exertions have been tabulated in Table 5.17

Table 5.17 Regression Equations for Perceived Force Exertions

	TRUE	Mean	Overall
Expert with Bare Hand	$AP=-1.441+8.775(\%MVC)-13.981(\%MVC)^2+7.662(\%MVC)^3$	$AP=-1.749+10.192(\%MVC)-16.114(\%MVC)^2+8.669(\%MVC)^3$	$AP=-1.988+11.424(\%MVC)-18.172(\%MVC)^2+9.732(\%MVC)^3$
Expert with Glove Hand	$AP=-1.393+8.303(\%MVC)-13.252(\%MVC)^2+7.339(\%MVC)^3$	$AP=-1.643+9.44(\%MVC)-14.847(\%MVC)^2+8.048(\%MVC)^3$	$AP=-1.579+9.162(\%MVC)-14.515(\%MVC)^2+7.93(\%MVC)^3$
Novice with Bare Hand	$AP=-0.645+5.283(\%MVC)-8.857(\%MVC)^2+5.213(\%MVC)^3$	$AP=-0.871+6.403(\%MVC)-10582(\%MVC)^2+6.04(\%MVC)^3$	$AP=-1.37+8.491(\%MVC)-13.809(\%MVC)^2+7.675(\%MVC)^3$
Novice with Glove Hand	$AP=-0.864+6.288(\%MVC)-10.77(\%MVC)^2+6.346(\%MVC)^3$	$AP=-0.795+5.942(\%MVC)-10.235(\%MVC)^2+6.089(\%MVC)^3$	$AP=-1.147+7.445(\%MVC)-12.662(\%MVC)^2+7.352(\%MVC)^3$

5.6.2. Validation of the Perceived Forces and Actual Force Models

The relational models for perceived forces and actual forces that were developed in section 5.6.1 were validated by computing the predicted perceived forces using the force data from a different set of 20 subjects. Pearson’s correlation coefficients for the predicted force values and the observed force values were computed for each test condition. Table 5.18 summarizes the correlation coefficients for each test condition.

Table 5.18 Pearson's Correlation Coefficient for Validation Data

	True	Mean	Overall
Expert with Bare Hand	0.8262	0.8608	0.9883
Expert with Glove Hand	0.8494	0.8645	0.9886
Novice with Bare Hand	0.7053	0.7195	0.9930
Novice with Glove Hand	0.7344	0.7683	0.9889

The correlation coefficients for the validation data identified a strong negative correlation between for the predicted and observed perceived forces for experts with gloved hand condition which establish that the regression model did not fit the validation data. Similarly, for novice with bare hand condition was also found to have a negative correlation which warrants further investigation.

CHAPTER VI

Conclusions and Discussions

This chapter discusses the results from this study. Effect of factors on force exertions and endurance time are first discussed. The second section discusses the different mathematical relations developed between forces and time of exertion. Accomplishment of research objectives are discussed in the next section. Finally the overall discussion on the study results provides limitations of this research with recommendations.

6.1 Effect of factors on Force Exertions

Preliminary study identified that forces exerted varied with hand condition, finger, subjects, and force levels. Consistent with this finding, force measurements for the modified pencil-hold task were also found to vary with hand condition, force level, finger and subjects who were nested under the group. An interesting finding from this research is that forces were not significantly different for expert and novice groups.

Findings from this research also identified that participants overexerted with glove use which reflects that gloves hinder tactile feedback affecting the critical sense of force balance. This result supports pervious glove research findings and establishes that development of ergonomic interventions should consider glove as an integral component of any dental task. Similarly, this research identified that maximum force is exerted with thumb than index and middle fingers during dental task performance. However, results from the preliminary study identified that maximum force was exerted with middle finger for the pencil-hold which supports that force exertions are reflective of the task characteristics. In the pencil-hold the tool is supported at the rigid interphalangeal joint of the middle finger but in the modified pencil-hold, the tool is held at the soft distal pad of the middle finger.

Another finding in this research is that the average force exerted for a simulated scaling task was 53.95% of the maximum voluntary contraction. This result contradicts the findings of Bramson et al (1998) who reported that the average scaling pinch force ranged between 11% and 20% of the peak pinch force. This variation in the average scaling force warrants further investigation of the scaling task.

6.2 Factor effects on Endurance Time

Factors that significantly affected endurance time were hand conditions, exertion level, group and subjects nested under group. During task performances different muscle groups contribute to force exertion which has been established in the previous section where force exertions were different for each finger. The longer endurance time with bare hand conditions further validates that people fatigue rate is higher with glove because of overexertion. This finding is consistent with earlier researches on glove fatigue and endurance time. Similarly, it was interesting to find experts having better endurance time that reflected the effect of clinical training to sustain forces. An important finding is that endurance time non-linearly decreased with exertion level for both bare hand and glove conditions for the modified pencil-hold. This result supports previous research findings that the relation between static exertion and time to fatigue follow a non-linear relation such as cubic (Rohmert 1960) or power (Garg et al 2002, Monod and Scherrer 1965) or exponential (Manenica 1986, Rose et al 1992, Deeb and Bishu 1991) functions.

6.3 Mathematical Modeling of Force Exertion and Endurance Time

The little to no information on the endurance time limit for precision gripping motivated this research to indentify one. Precision gripping being commonly employed in healthcare industries, dentistry in particular encouraged this research to evaluate a representative task that involve forceful pinching. From published literature endurance limits for task performances have been established through the development of force-endurance models which is the main objective of this research.

The models reported in this dissertation are based on mean force proportions. However, recommendations on endurance time have been made using overall force proportions as it provided orderly results. Table 6.1 summarizes the endurance time for the different test conditions.

Table 6.1 Endurance Time Limits for Simulated Dental Task

	Endurance Time (sec)			
Exertion Level (%MVC)	**Experts with Bare Hand**	**Experts with Glove Hand**	**Novice with Bare Hand**	**Novice with Glove Hand**
10	84.59	46.62	106.64	192.06
20	69.34	49.10	79.51	125.19
30	61.80	52.16	64.04	82.64
40	59.45	54.90	57.01	59.01
50	59.77	56.44	55.20	48.88
60	60.25	55.90	55.39	46.85
70	58.38	52.39	54.37	47.51
80	51.63	45.02	48.92	45.45
90	37.50	32.91	35.82	35.26
100	13.45	15.17	11.85	11.53

Based on the recommendations, it is evident that endurance limit for experts is 40%MVC and 50%MVCfor novices employing modified pencil-hold. The main motive of this research is to identify a time limit for scaling task which was identified to be 56.5 seconds.

6.4 Mathematical Modeling of Perceived and Actual Forces

The primary goal of this research is to develop force-endurance curves and identify an endurance limit for modified pencil-hold tasks. The task performed to develop the force-endurance curve involves perceived sub-maximal level of exertion. Most tasks are performed at perceived sub-maximal levels with little to no feedback. Force perception, critical for understanding muscular fatigue, is affected by many factors including gloves, tool characteristics, work characteristics and environment. Lack of information on force perception motivated this research to identify a relation between perceived (actual) forces and theoretical (%MVC) forces.

Regression modeling techniques were employed to establish the relation between actual force levels and theoretical force levels. Force proportions were used to develop the models as true forces measured in pounds have high variability. Models were developed for true force proportions, mean force proportions and overall force proportions. The best fit model was selected based on Akaike’s information criteria (AIC) values. From the analysis, the relation between perceived force and theoretical force was found to follow a cubic function for both experts and novice with bare hand and gloved hand conditions.

In this dissertation, models that were developed using mean force proportions have been reported. However, models developed with overall force proportions have been used to make recommendations on exertion levels not evaluated in this dissertation. Figure 6.1 shows the recommendations for perceived exertion levels for experts and novice with bare and glove hand.

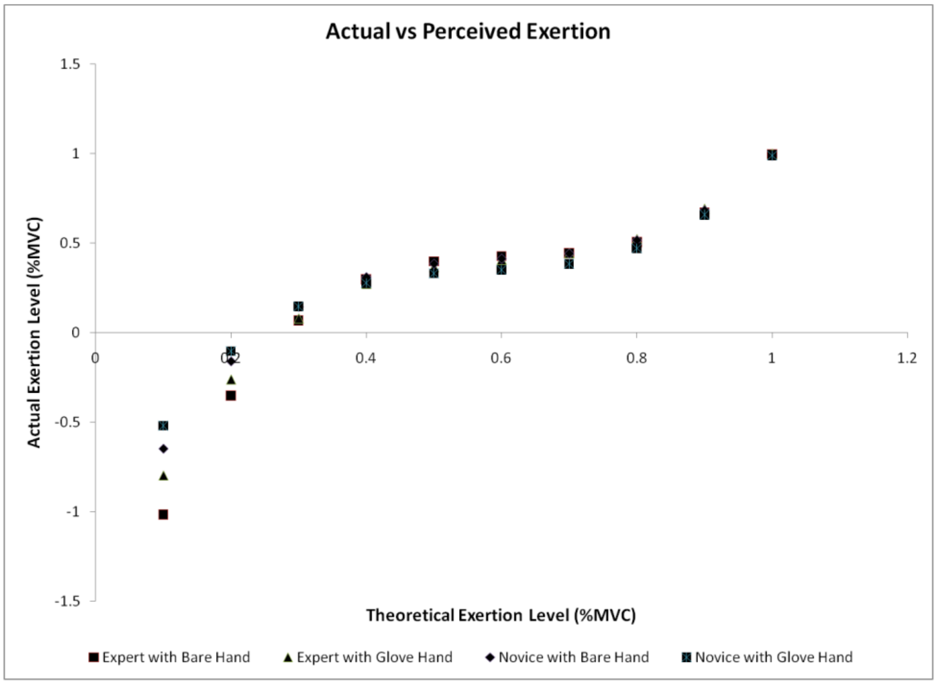

Figure 6.1 Recommendations for Perceived Exertions

Based on recommendations, it is evident that people underestimate sub-maximal exertion levels. Most sub-maximal exertions are perceived less than 50% of the maximum voluntary contraction. This finding will have greater implications in future tool design and task design. Similarly, from the models developed in this dissertation, it is identified that people miscalculate forces for just-hold type of tasks. Findings from this research are also expected to influence safety measures that must be taken for task performed at sub-maximal levels.

6.5 Realization of Research Objectives

The purpose of this research is to identify how long can dental hygienists attend to patients before the onset of fatigue. This basic research question was addressed with four specific objectives based on force exertions: (1) Identification of a force level for a representative dental hygiene task, (2) Development of force-endurance curves for bare hand, (3) Development of force-endurance curves for thin-gauge gloves, and (4) Modeling of perceived sub-maximal force level with theoretical force levels.

The first objective of this research was realized by evaluating a simulated periodontal scaling task. The periodontal scaling task was evaluated as published literatures identified that scaling task was the most common task performed by a dental hygienist. From the evaluations, the average force exertion level for the scaling task was identified to be 54% of the maximum voluntary contraction. The average scaling exertion level was accommodated within the force-endurance model by establishing the limiting exertion level to be 40%MVC for model development.

The main objective of this dissertation is the development of force-endurance models for pencil-hold tasks. Published literatures on hand performances have established a significant performance variation with bare hand and gloved hand conditions. For this reason, separate objectives were established to develop force-endurance models for bare hand (objective 2) and gloved hand conditions (objective 3). Variance analysis of force and time data identified a difference in performance of experts and novice with bare hand and gloved hand. Therefore, separate force-endurance models were developed using regression techniques for experts with bare hand, experts with gloved hand, novice with bare hand and novice with gloved hand. The models were developed from the force time data from forty (20 experts and 20 novice) random participants. Cubic force-endurance models were developed for all conditions. The models were further validated using correlation analysis with good correlation between the predicted and observed values. Validation of the models was performed using data from a different set of twenty (10 experts and 10 novice) participants.

The final objective of modeling perceived forces with theoretical forces was performed to identify the force perception. Modeling the force-perception identified that people underestimated sub-maximal levels of exertion with the relation between perceived exertion level and theoretical exertion level being cubic in nature.

In summary, initial efforts have been made to answer the research question of how long can dental hygienists attend to patient's needs before the onset of fatigue. The findings from this research are based on force exertion and are pertinent to the conditions evaluated in this study.

6.6 Overall Discussion

Lack of information on endurance limit for precision gripping that is commonly employed by dental professionals motivated this research to establish a force endurance model for a representative healthcare task. Realization of force exertions in precision gripping was necessary for this research which was accomplished in a preliminary study that was supported by a grant from National Occupational Research Agenda (NORA). Results from the preliminary study provided direction in the selection of force sensors and to establish the main research methodology. Scaling task was identified and evaluated as the representative dental hygiene task. The results from scaling task helped in realizing the main objective of developing force-endurance models using regression techniques and correlation analysis. Similarly, the relation between perceived exertion and theoretical exertion were developed and validated using regression techniques and correlation analysis. In conclusion, endurance limit for scaling task has been identified in this research. The results from this study will have implications on tool design, task design and task safety measures.

6.7 Limitations and Future Research:

The main limitation of this study is that it considers only force exertions to establish the endurance limit for precision gripping. However, factors such as posture and other task characteristics should considered in future research to establish an accurate endurance limit. The other limitation of this dissertation is that participants were primarily students in both the expert and novice groups. It is necessary to evaluate practicing dental hygienists to identify the true endurance time. Models developed in this dissertation included only static exertions but actual dental tasks are dynamic and are influenced by other factors that contribute to muscular fatigue. Future research should evaluate other thin gauge glove performances and their effect on endurance time as American Dental Association recommends the use of nitryl gloves and other polymer based gloves.

6.8 Contribution to the Body of Knowledge

This research is first of its kind on precision grasps. The findings from this research have greater implication on healthcare industries where precision grasps are commonly employed. The information presented in this dissertation is expected to influence tool design and will make inroads towards healthcare education. Establishment of an endurance limit will also allow management and engineers to determine work-rest cycles that will contribute to the wellbeing of the dentists. The concepts presented in this dissertation needs to be extended to other healthcare tasks particularly to that of surgeons who meticulously work to maintain a healthy society.

CHAPTER VII

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APPENDIX I

Determination Of Relation Between Actual Contact Force At Hand/Glove Interface And The Grasp Force For A Set Of Standardized Pinch And Pencil Hold Tasks.

Abstract

Health care professional are exposed to sub-maximal exertions while tending to the patients’ needs. Their performance can be further hindered with the use of thin gauge gloves. This study attempts to capture data on the force exerted to perform a three-finger grasping tasks. Initially, the study attempts to develop a methodology for the same. Two subjects participated in the development of the force measuring methodology and twenty subjects (10 males and 10 females) participated in the actual experiment. Force sensing resistors were used to record the force fixed at the distal phalanges of the thumb, index and middle fingers. The results indicate that performance was better with bare hand followed by latex, vinyl and nitryl gloves. The force exerted was more than the force needed with the ratio (force exerted/force needed) more at lower levels of sub-maximal exertion. Another important finding of this study is the non uniform distribution of forces along the middle finger, thumb and index finger. People exert more on middle finger as compared to the others two fingers.

Introduction

Gloves are used to protect the hand from external trauma. However, they deteriorate hand performance. Bensel (1993) conducted an experiment in which the effects of three thicknesses (0.18 mm, 0.36 mm, 0.64 mm) of chemical protective gloves were investigated using different dexterity tests. The author identified a negative linear relationship between glove thickness and dexterity. Nelson and Mital (1994) found no appreciable differences in dexterity and tactility among latex gloves of five different thicknesses: 0.2083 mm; 0.5131 mm; 0.6452 mm; 0.7569 mm; and 0.8280 mm. Neiburger (1992) on studying the tactile performance of medical examination gloves reported a 36 percent reduction in tactility when subject donned gloves. Cochran et al (1986) examined the differences in grasp force degradation among five different types of commercially available gloves as compared to a bare handed condition. They found that the bare handed grasp force was significantly higher than any of the glove conditions. Shih et al (2001) assessed the impact of multiple layered gloves on tactile sensitivity using discriminating tests (two-point discrimination test and Von Frey hair test). It was observed that multiple layers of gloves impaired haptic sensitivity. Grip and load forces were recorded for picking various masses (100, 150 and 200g) using force transducers. Greater grip and load forces were identified for multiple layered gloves. They demonstrated that the gloves were more slippery than bare hand due to lower friction between the object and glove surfaces. Buhman et al (2000) examined the grasp force at maximal and sub-maximal exertion. They found that the glove effect was strong at maximal exertions but marginal at sub-maximal exertions. From the findings they concluded that the neuro-muscular mechanisms utilized during maximal exertions are different from those used during sub-maximal or 'just holding' types of exertion.

At the University of Nebraska-Lincoln, considerable work on sub-maximal exertion has been performed. When grasping at sub-maximal levels, it is typical that people overexert initially to a peak level and then slowly reduce the grasp to a stable level (Bishu *et al*. 1994, Bronkema *et al.* 1994, Kim and Bishu 1997). There are three relevant issues here: a) relationship between peak force and stable force, b) relationship between stable force and load grasped, and c) grasp control during grasping. The ratio of stable force to load lifted tends to be high at the low levels of loads and decrease as the load grasped increases as shown in Table 1 (Bronkema *et al.* 1994, Bishu *et al.* 1994).

Table 1 Load Effect on peak and stable forces (Bronkema *et al.* 1994)

Load	Peak Force	Stable Force	Ratio of stable/load
0.5	15	9.6	19.2
5.5	22	17	3.1
10.5	29.7	22	2.1
15.5	35	29	1.9
20.5	40.8	34	1.7

Wilhelm and Bishu (1997) examined the stability of grasp force at various levels of exertions and hand conditions (Wilhelm and Bishu 1997). The authors defined the stability as grasp control, and measured it by the amount of variance of grasp force. A larger variance implied less stability of the grasp force. Control appears to be better at lower loads than at higher loads (Figure 1).

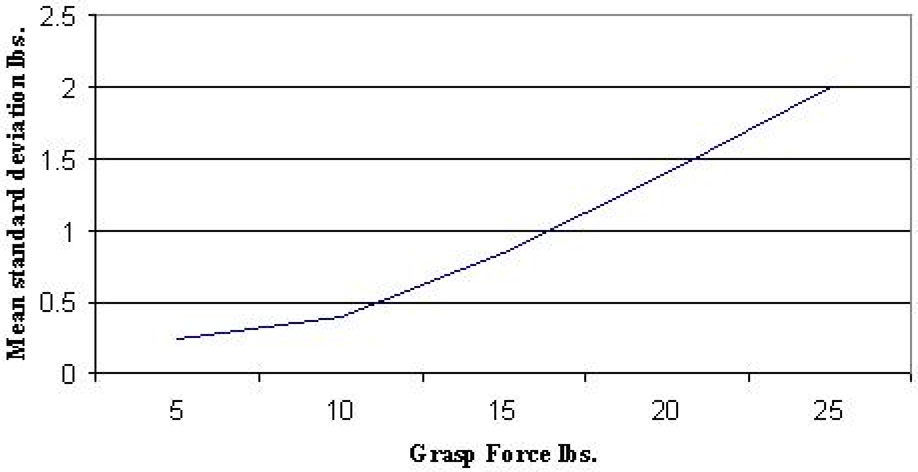

Figure 1: Grasp force effect on grasp control (Wilhelm and Bishu 1997)

Bronkema and Bishu (1996) investigated the effect of friction on grasp force by applying two different sizes of silicone pads to glove surface (Bronkema and Bishu 1996). The application of silicon to the surface of the glove significantly affects the peak and stable holding force, with the ratio of peak to stable force reducing with increasing friction. *The main research question that this study addressed was to determine if exertion pattern in pinch tasks are similar to grasping tasks. Should this be so, then people will exert more force than what is needed in pinch tasks as well*

Specific aims:

1. To develop a methodology for determination of force developed along the palmar surface of the hand with and without gloves, while performing ‘three finger pinching tasks’
2. Using the above determined methodology, to determine the relationship between actual contact force at hand/glove interface and the grasp force for a set of standardized pinch and pencil hold tasks.

Method:

FlexiForce® 0-25lb force sensing resistors (FSR) backed with a data logger were used to capture the force exertions. The experiment consisted of two parts, (1) development of a methodology to capture forces at both finger-glove and glove-object interfaces simultaneously, and (2) determination of finger force exertion for a set of standardized pinch tasks and pencil-hold task.

Calibration of FSR

Prior to the use of the FSR, an appropriate calibration procedure was needed. In an effort to simulate the conditions, it was initially calibrated subjectively. In this method 2 subjects were asked to apply force in steps of 0.4 kg up to 2.4 kg on a digital kitchen balance. The FSR was fixed to the distal phalange of the subject's thumb, index and middle fingers. This method calibrated the FSR from 0.8lbs to 6lbs. A common calibration equation could not satisfy all the conditions tested. A number of equations had to be developed, one for each condition. Table 2 shows the list of calibration equations developed using this method.

Table 2 Calibration equations using subjective method

Finger	Hand Condition	Calibration Equation
Thumb	Bare	Applied Load = 2.064+8.519 (FSR Reading)
	Glovein	Applied Load = 1.225+12.827 (FSR Reading)
	Gloveout	Applied Load = 1.589+34.444 (FSR Reading)
	In	Applied Load = 1.213+18.612 (FSR Reading)
	Out	Applied Load = 1.504+18.039 (FSR Reading)
Index	Bare	Applied Load = 1.783+4.318 (FSR Reading)
	Glovein	Applied Load = 1.417+5.5 (FSR Reading)
	Gloveout	Applied Load = 1.051+25.088 (FSR Reading)
	In	Applied Load = 1.408+7.378 (FSR Reading)
	Out	Applied Load = 1.066+16.189 (FSR Reading)
Middle	Bare	Applied Load = 1.434+6.744 (FSR Reading)
	Glovein	Applied Load = 1.465+7.089 (FSR Reading)
	Gloveout	Applied Load = 0.444+62.858 (FSR Reading)
	In	Applied Load = 0.996+11.364 (FSR Reading)
	Out	Applied Load = 0.645+23.344 (FSR Reading)

Due to these issues, a different method of calibration was sought. This was using a Universal Testing Machine (UTM). In this method a compressive force was applied using a probe with a diameter equal to the sensing area of the FSR. Table 3 shows the calibration equation developed using this method. The limitation with this method was the inability to apply a constant load on the sensor. For this reason, yet another calibration method was sought.

Table 3 Calibration equation using UTM

FSR	Equation
1	Applied Load = -0.0925+1.794 (FSR Reading)
2	Applied Load = -0.0925+2.559 (FSR Reading)
3	Applied Load = -0.0925+2.349 (FSR Reading)
4	Applied Load = -0.0925+1.966 (FSR Reading)

In this method, a simple beam setup was used to calibrate the FSR using dead weights. A simply supported beam setup was built using wooden plank. The setup was designed to nullify the moments at one the supports (Support B). The FSR was fixed at the other support (Support A). Figure 2 shows the beam setup. Dead weights were applied at end where the FSR was fixed.

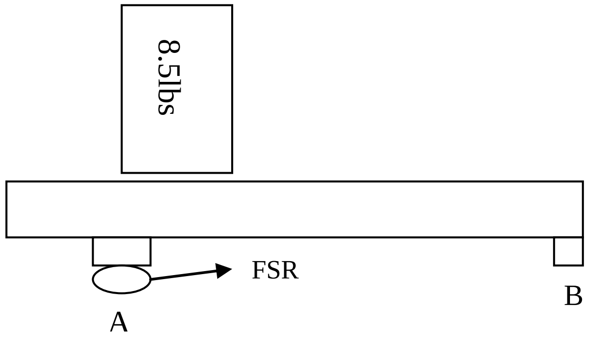

Figure 2 Beam setup for FSR calibration

The FSRs were calibrated for a range of 0-8.5lbs. Weights were applied in steps of 20 seconds between load applications. Regression analysis was performed to obtain the relation between applied force and measured force. A separate calibration equation was developed for each FSR. Table 4 gives the calibration equation developed.

Table 4 Calibration equations using Beam setup

FSR	Calibration Equation
Thumb	Applied Load = 0.432 + (0.031 x FSR Reading)
Index	Applied Load = 0.442 + (0.032 x FSR Reading)
Middle	Applied Load =1.157 + (0.023 x FSR Reading)

Development of Force capturing methodology

A primary objective of this study is to develop a methodology to capture the finger force using FSR. This part of the experiment was performed using 2 subjects and one glove condition. Subjects were asked to exert 2, 4 and 6 lbs force on a B&L Engineering pinch gauge. The calibrated FSRs were fixed at the distal phalanges of the thumb, and index fingers of the dominant hand. Various locations for the FSR's were tried as under:

- *BARE:* FSRs were fixed to the distal phalanges of the thumb, and index finger of the subject
- *EBARE:* FSRs were fixed on the pinch gauge and bare hand pinch force was recorded.
- *GLOVEOUT:* Force exerted with the FSRs fixed over the glove at the distal phalanges of the thumb, and index finger
- *GLOVEIN:* Force exerted with FSRs fixed at the hand glove interface of the distal phalanges of the thumb, and index finger
- *IN:* FSR reading at the hand glove interface when the glove is sandwiched between 2 FSRs
- *OUT:* FSR reading at the glove equipment interface when the glove is sandwiched between 2 FSRs

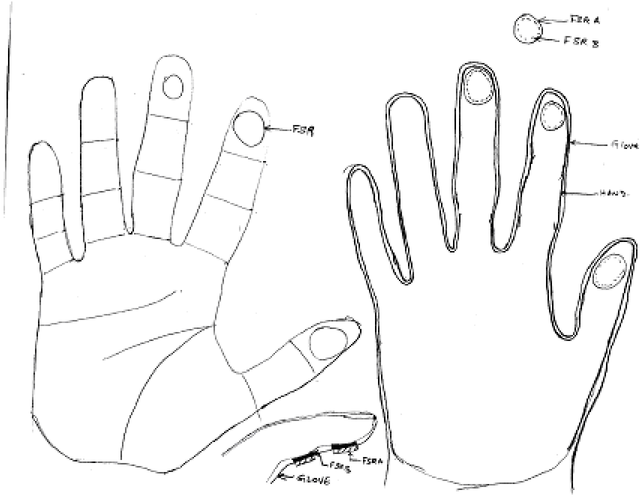

Figure 3 FSR locations on hand

Figure 3 shows the location of the FSR for the different hand conditions. Table 5 shows the force measurement recorded for the two subjects, in all the conditions. It is seen that the readings are all over the place, perhaps due to the strain gauge (FSR) rolling during measurement. Hence, it was decided not to measure force exertion at both the interfaces simultaneously.

Table 5 Force measurement for different hand conditions

Applied Load	**Hand Condition**	**SUBJECT1 FSR Reading (lbs)**	**SUBJECT2 FSR Reading (lbs)**
2lbs	**Bare**	0.462	0.21875
	Ebare	0.3	0.2875
	Gloveout	0.331	0.3625
	Glovein	0.30625	0.13125
	In	0.95	0.1125
	Out	0.93125	0.60625
4lbs	**Bare**	1.1875	0.5
	Ebare	0.9375	0.7125
	Gloveout	0.95	0.69375
	Glovein	0.8	0.36875
	In	0.675	0.175
	Out	1.73125	0.68125
6lbs	**Bare**	1.65	1.1625
	Ebare	1.5625	1.21875
	Gloveout	1.29375	0.95625
	Glovein	1.24375	0.50625
	In	1.15625	0.35
	Out	2.44375	0.95

Determination of Finger Force for Pinch and Pencil Hold Tasks

A total of twenty subjects (10 males and 10 females) performed this experiment. Subjects were students from the College of Engineering at the University of Nebraska-Lincoln. Prior to the experimentation, subjects were explained about this research and filled an informed consent form to participate in this study. The subjects were asked to perform a standard three-jaw chuck pinch and pencil hold for four hand conditions (Bare hand, Vinyl glove, Latex glove, and Nitryl gloves).

Pinch Task

For this task, FSRs were fixed to the distal phalanges of the thumb, index and middle fingers. The subject was asked to exert and hold 1, 3 and 5 lb on a B&L Engineering Pinch Gauge for 30 seconds. ***For the gloved hand condition, force exertions within the glove and glove-equipment interface were measured as separate trials.*** Subjects were provided with a minute break between trials to minimize finger fatigue. Each subject performed two repetition of each condition.

Pencil Task

For the pencil hold task, two FSRs were fixed to the distal phalanges of the thumb and index finger and the third FSR was fixed at the third inter-phalangeal joint of the middle finger. Subjects were asked to exert and hold the maximum pressure to hold a pen for 5 seconds. Similar to the pinch task, forces were recorded for the bare, vinyl, latex and nitryl gloved hand conditions. Each subject performed two repetition of each condition.

Results

Determination of Pinch Force:

For the analyses, measured force was the dependent variable while hand condition, force exerted and FSR locations were independent variables. Analysis of variance (ANOVA) indicated a significant effect of all the independent variables and their two-way interactions. Tbale 6 shows the ANOVA summary.

Table 6 Summary of ANOVA for pinch task

Factors	Pinch force
Subject	**
Condition	**
Finger	**
Force	**
Subject x condition	**
Subject x Finger	**
Subject x Force	**
Condition x Finger	**
Condition x Force	**
Finger x Force	**

** Significant ($\alpha = 0.05$)

Comparing the force exertion for the different hand conditions and force levels, a significant variation at higher force level and little variation at lower levels was evident for the different hand conditions. Figure 4 shows the force exertion for the different hand conditions

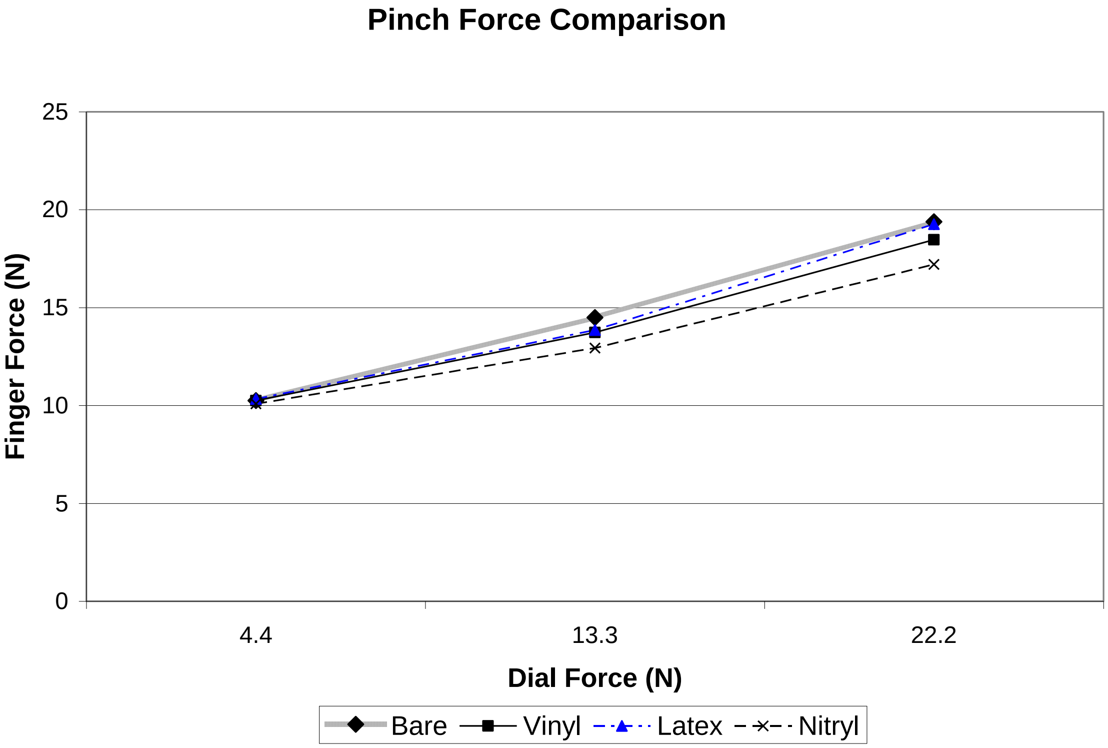

Figure 4 Force exertions for different hand condition

At higher exertion level, latex gloves tend to behave similar to the bare hand which is in support of earlier researches on latex gloves. The results also support the findings of Gnaneswaran et al (2005) that subjects tend to exert more with latex gloves than with vinyl. It is interesting to note that the findings on the ratio of force exerted to force needed. Figure 5 shows the force-ratio at the different levels of exertions. The data appears to be very similar to our findings on sub maximal grasp (Table1 above).

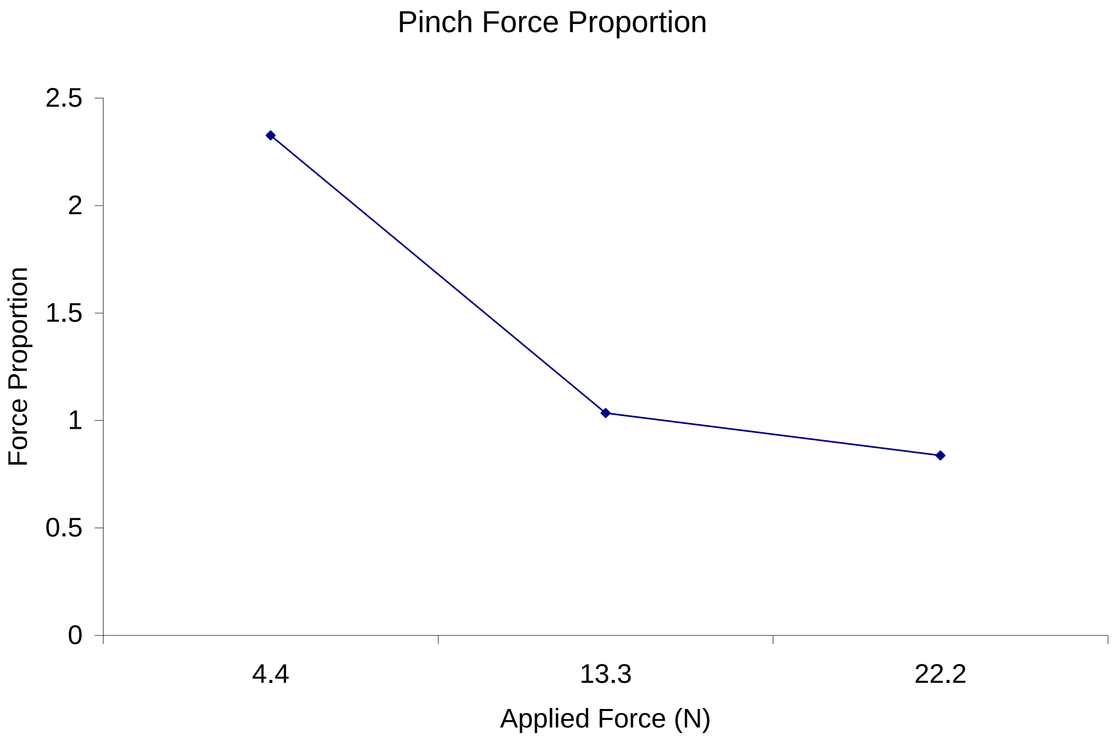

Figure 5 Force-ratio for sub-maximal exertion

For the above figure, it can be said that subjects apply greater force at low loads and a stable force at higher loads. The results from this study are consistent with earlier studies (Bronkema *et al.* 1994, Bishu *et al.* 1994) on grasping. Table 7 shows the individual finger force exertion for the different hand conditions at different levels of exertion.

Table 7 Average finger force exertion

		Force (N)		
	Finger	**4.4**	**13.3**	**22.2**
Bare	**Thumb**	2.352	4.267	6.290
	Index	2.236	2.931	3.585
	Middle	5.666	7.293	9.512
Vinyl	**Thumb**	2.419	4.006	6.133
	Index	2.290	2.813	3.535
	Middle	5.542	6.913	8.802
Latex	**Thumb**	2.387	4.011	6.575
	Index	2.275	3.022	3.893
	Middle	5.674	6.819	8.794
Nitryl	**Thumb**	2.292	3.575	5.232
	Index	2.153	2.739	3.544
	Middle	5.643	6.621	8.434

It is interesting to note that distribution of forces is not uniform. People appear to exert more from middle finger that the other two fingers. This pattern appears to be consistent across all loads tested here. Figure 6 shows the finger force distribution for the different hand conditions (This is the plot of data shown in Table 6).

In summary, the two main findings of this study are,

1. People overexert with the extent of overexertion is more at lower levels than higher level of load
2. Distribution of force exerted on fingers is not uniform with more force exerted by middle finger as compared to other two.

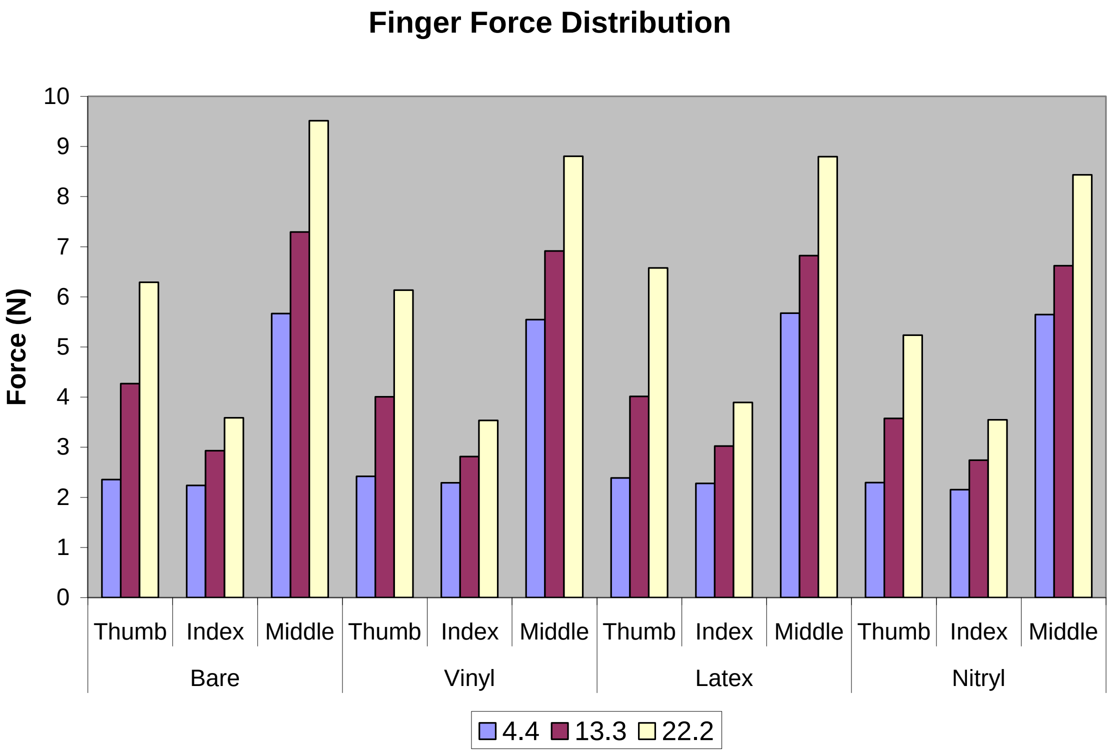

Figure 6 Pinch force distribution for different hand conditions

Pencil Task

Analysis of Variance (ANOVA) was performed to identify the significant factors contributing to the pencil hold task. Table 8 shows the summary of ANOVA.

Table 8 Summary of ANOVA for Pencil-hold

Factors	Pencil force
Subject	**
Condition	**
Finger	**
Subject x condition	**
Subject x Finger	**
Condition x Finger	**

** Significant ($\alpha = 0.05$)

The results of this analysis were similar to that of the pinch force analysis. All the main and interaction effects were significant. Figure 7 shows the force exerted to hold a pen for the different hand conditions.

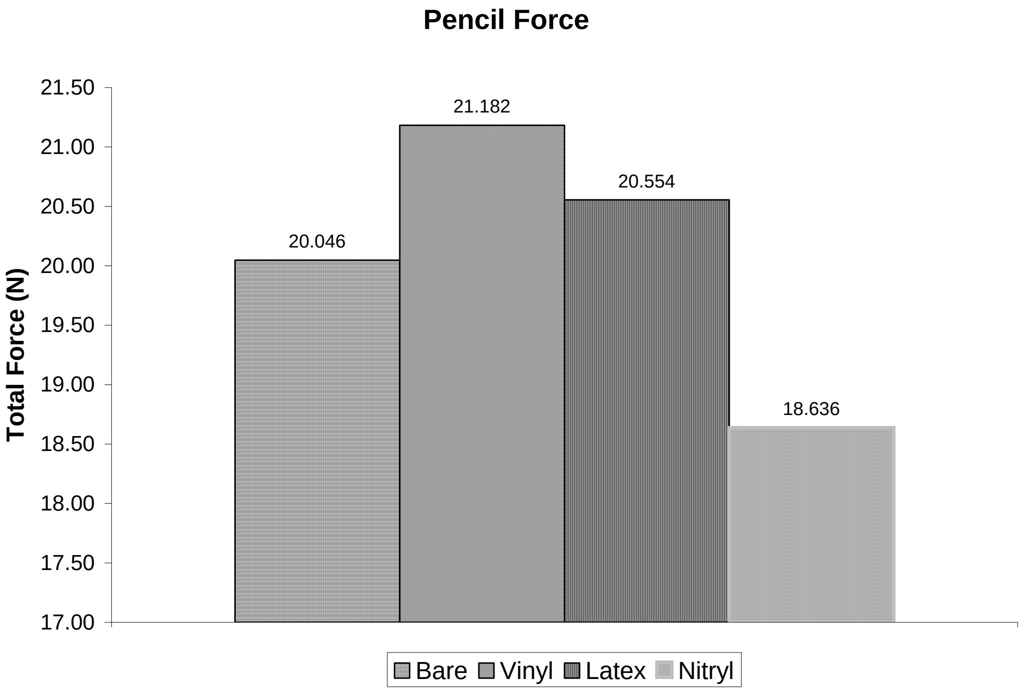

Figure 7 Pencil force exertion for different hand conditions

Similar to the earlier findings, nitryl glove was found have lower mean value than the others. The reason for such a variation may be due to material properties and thickness of the nitryl glove which hinders the tactile feedback. Figure 8 shows the finger force distribution for the pencil hold task. From the graph it is evident that force exerted by the middle finger is more due to the location of the pen when holding. The middle finger acts as a support to the force exerted by the thumb and index finger. The low values of index finger indicate its primary use for manipulation and its orientation on the hand.

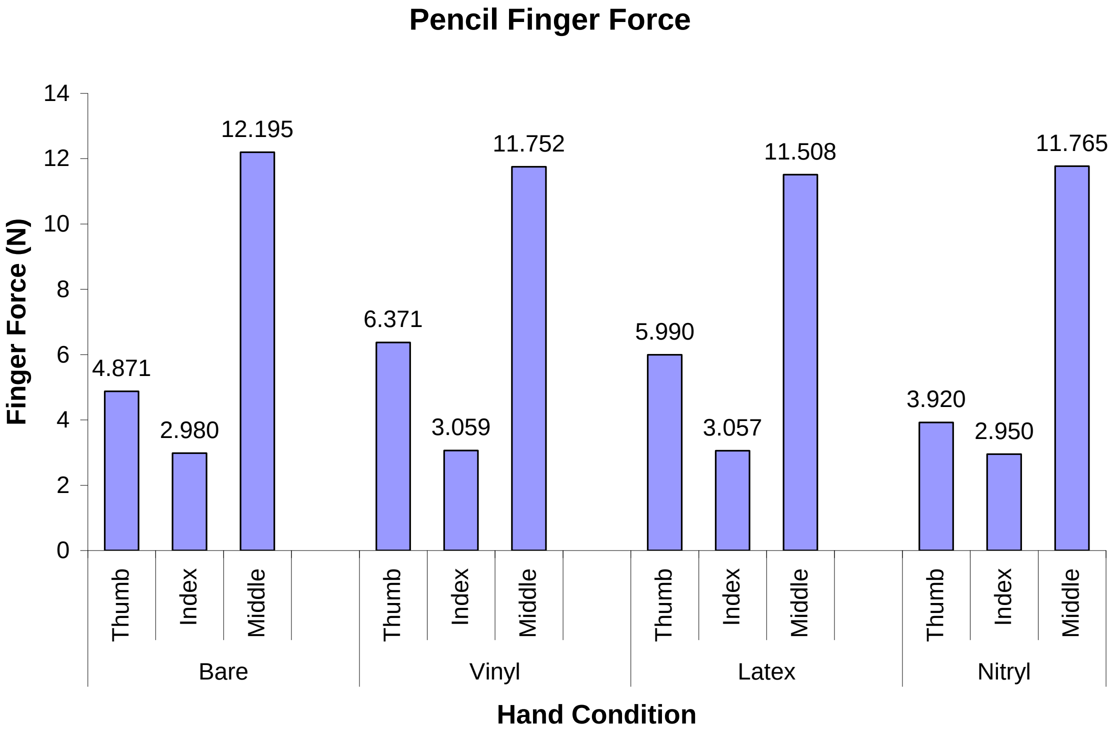

Figure 8 Pencil force distribution

Conclusion

There were two main objectives of this study. The first was to establish a methodology for measuring contact force at hand/glove/equipment interface, and the second was to measure forces, using the methodology established to measure contact force in pinching and pencil hold tasks. Force sensing resistors are not the best tool for measuring forces. They roll considerably during experiment. It was initially proposed to measure the force both at the hand-glove interface and glove-equipment interface simultaneously. This task was not performed because of operational difficulty in aligning the FSR during the task performance. A possible reason for the rolling of the sensor is the difference in frictional forces at the hand-glove and glove-equipment interfaces. Also the FSR's were highly region specific. The sensor captured the force exerted within its sensing area of 10mm^2. Any other force applied outside the sensing area is not captured.

Though care has been taken to capture the force, use of other types of sensors such as the Finger TPS® using a capacitance principle will better suite the purpose. The Finger TPS® is designed to capture the force exerted in the distal phalanges of the fingers and be conveniently worn on fingers without any hindrance to performance. Distribution of force exerted on fingers is not uniform with more force exerted by middle finger as compared to other two. This has a large ramification for glove designers

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