

United States
Department of
Agriculture

Forest Service

Technology &
Development
Program

5100—Fire Management
May 2000
0051 1201—SDTDC



Biomechanical Analysis of Grubbing Technique in the Use of Fire Hand Tools



Biomechanical Analysis of Grubbing Technique in the Use of Fire Hand Tools



**Lois P. Sicking
Mechanical Engineer***

San Dimas Technology and Development Center
San Dimas California 91773-3198

* In addition, the author is licensed to practice as a Registered Nurse in the states of California and Texas, with Advanced Cardiac Life Support (ACLS) certification by the American Red Cross.

Information contained in this document has been developed for the guidance of employees of the Forest Service, USDA, its contractors, and cooperating Federal and State agencies. The Department of Agriculture assumes no responsibility for the interpretation or use of this information by other than its own employees. The use of trade, firm, or corporation names is for the information and convenience of the reader. Such use does not constitute an official evaluation, conclusion, recommendation, endorsement, or approval of any product or service to the exclusion of others that may be suitable.

The US Department of Agriculture (USDA) prohibits discrimination in its programs and activities on the basis of race, color, national origin, sex, religion, age, disability, political beliefs, and marital or familial status. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA Office of Communications at 1-202-720-2791 (voice), or 1-800-855-1234 (TDD).

To file a complaint, write the Secretary of Agriculture, US Department of Agriculture, Washington, DC 20250, or call 1-800-245-6340 (voice), or 1-800-855-1234 (TDD). USDA is an equal employment opportunity employer.

Acknowledgements

This report is the result of the efforts of many Forest Service employees, retired Forest Service specialists, contractors, and cooperating Federal and State agencies. In addition, the following people have contributed:

Bob Serrato

Region 5

Dalton Interagency Hotshot Crew Superintendent

Tony Sciacca

Region 3

Prescott Interagency Hotshot Crew Superintendent

David Conklin

Region 5

Bear Divide Interagency Hotshot Crew Superintendent

Phillip Cheetham

Ph.D. Candidate Biomechanics

Arizona State University

Eric Mallett

Ph.D. Candidate Biomechanics

Arizona State University

Brian J. Sharkey

Ph.D. Exercise Physiology

University of Montana



A special measure of gratitude and mention goes to the family of **Art Jukkala** for his efforts with this project, especially in field testing, and the review of the test plans and reports.

TABLE OF CONTENTS

INTRODUCTION AND SCOPE	1
PREVIOUS FIRE TOOL STUDIES	1
ERGONOMIC CONSIDERATIONS	3
Carpal Tunnel Syndrome	4
Low Back Pain	5
ERGONOMIC FACTORS	
Grip Strength	6
Physical Fitness	7
BIOMECHANICAL TEST PARAMETERS	8
TEST PROCEDURE AND INSTRUMENTATION	8
Test Tools	9
Preparation for Testing	10
Detailed Test Method	11
Determination of Skilled and Regular Firefighters	12
DETAILED DATA ANALYSIS BY TOOL	12
Standard Pulaski	13
Super Pulaski	20
Combi Tool	28
DETAILED DATA ANALYSIS BY BIOMECHANICAL PARAMETER	
Tool Acceleration/Force At Impact	35
Tool Lift Height	35
Work Cycle Time	36
Hand Separation	36
Wrist Rotation Joint Angle Profile	36
Shoulder Extension Angle and Arm Reach	39
Critical Biomechanical Parameters	42
Proposed Training Program	42
Participant Ranking of Tools	45
Experience, Strength, and Fitness Scores	46
Participant Comments	47

DISCUSSION	47
CONCLUSIONS.....	48
RECOMMENDATIONS	53
BIBLIOGRAPHY	55
APPENDIXES	
A. Definitions	59
B. Fire Hand Tool Test Matrix	61
C. Biomechanics of Fire Hand Tools Test Matrix	63
D. Preference Rating of Hand Tools	65
E. Biomechanical Angle Profiles and Angular Velocity Profiles	67
F. Biomechanical Tables of Values	69

INTRODUCTION AND SCOPE

Ergonomics is the study of optimizing the human tool system, thereby reducing the potential for injury, improving safety, and increasing productivity. Ergonomic principles can be used to prevent or minimize injuries in firefighters using fire hand tools in wildland firefighting. The emphasis is on changing the tool, user technique, and environment rather than changing people to fit the tool. In this way priority is given to the capabilities, needs, and limitations of people. A minimum performance standard based on job physical requirements is fundamental. Ergonomics, sometimes called human factors, discovers and applies information about human behavior, abilities, limitations, and other characteristics to the design of tools, machines, systems, tasks, jobs, and environments for productive, safe, comfortable, and effective human use (1).

There has been a progressive effort to evaluate and redesign hand tools used in wildland fire service for fireline construction. In recent years, fire tool testing by the San Dimas Technology and Development Center (SDTDC) has focused on tool design and most recently on firefighter biomechanics.

Biomechanical measurements provide insight into the abilities and limitations of the human body while generating grubbing motions with fire hand tools. Identification of the optimum biomechanics associated with the use of hand tools can contribute to improvements in performance with a reduction in ergonomically induced injuries. SDTDC was tasked to:

- Conduct a biomechanical evaluation of firefighters using fire hand tools
- Determine the critical biomechanical parameters associated with grubbing
- Describe the biomechanics of regular and skilled grubbing technique

- Conduct a comparative analysis of regular and skilled grubbing technique
- Report findings.

This information can be used to train firefighters for ergonomic efficiency, improved performance, and increased worker safety. In addition, hand tool design modifications were derived from these kinematic measurements.

The standard Pulaski, Super Pulaski, and Combination (Combi) hand tools were tested with a sample size of 22 firefighters. Applicable biomechanical parameters were determined to be left and right shoulder joint angle profiles, wrist range of motion, joint angular velocity profiles, peak angular velocities, body posture at maximum tool lift height and tool impact, motion cycle time, tool lift height, tool head path, and tool acceleration/force on impact. Definitions of terms relative to the context of this report are provided in Appendix A.

PREVIOUS FIRE TOOL STUDIES

Fire tool testing by the Missoula Technology and Development Center (MTDC), as described in *An Improved Wildland Fire Fighting Tool*, included a field evaluation, with efficiency defined as the amount of fireline in feet versus the amount of energy expended to produce fireline. Productivity was in terms of feet per minute. The Combi tool was described in this study as a multipurpose fire hand tool with a higher level of productivity as compared to the standard and Super Pulaski. It was reported that the Super Pulaski had a high energy cost in relation to the increase in production. There also was a safety concern. Firefighters with a poor grip and decreased upper body strength had a greater potential for injury with the use of the Super Pulaski (2).

National interest propelled an initial study by SDTDC regarding tool redesign (3). This combined qualitative and quantitative study compared the hoe blade of commonly used grubbing tools to include the mini, standard and Super Pulaskis, and the standard Pulaski with a fiberglass handle. The goal was to determine tool configurations that best balanced physiological characteristics with optimum production of fire line and firefighter safety. Although several areas of refinement were needed, the study concluded that regardless of individual size, physical condition, or rate at which a firefighter grubs, the Super Pulaski could produce more line than the standard or mini Pulaski tools. However, the energy costs were much higher than the increased output. In addition, a safety concern was identified associated with the increase in the tool head mass of the Super Pulaski. An increase in tool head mass increases angular acceleration during the down swing phase of motion, resulting in an increase in tool rotation on impact, with an increase in stress on the wrists. In other words, the heavier the tool head, the greater the tendency to twist especially when the tool head hits the ground. This is felt as a stinging sensation of the hands and increased fatigue in the wrists.

A fire tool survey of the Interagency Hotshot Crew (IHC) network was conducted by SDTDC prior to the initial study in order to collect information, hardware, and drawings on standard, modified, and specialty fire hand tools in service. This survey revealed that the Pulaski was the most common fire tool in use and the most common fire tool modified.

Modifications typically increased blade width, as in the Super Pulaski, which increased tool head mass, and raised a safety concern. Consequently, the standard and Super Pulaski were selected for further study. The Combi tool was included as the reference grubbing tool for comparison based on high productivity rates.

The benefit derived from this initial study was that applied scientific methodology provided a positive contribution to the tool selection process (4). Efforts from this study resulted in the development of a procedure for hand tool evaluation; an efficiency rating of hand tools based on field test performance, measuring grubbing tool production in terms of weight of material moved per unit of time, against ergonomic input in terms of calories per unit of time expended; and a preference rating of hand tools based on subjective responses/opinions of the test workers (3).

Kinematic testing was proposed in order to evaluate the potential for tool design, expanding the research and tool evaluation efforts recommended in the initial study. An investigation revealed that new technology in measuring human-tool kinematics had been developed and was commercially available. Field testing was conducted with the magnetic motion capture/analysis system as indicated in figure 1. It was determined that this system had practical applications in fire tool studies. It was further noted from a preliminary biomechanical analysis that the motions of a skilled firefighter varied significantly from those of a regular firefighter. There was a wide variance in tool swing technique/motions and body posture, in terms of bend-over angle, shoulder position, grip, separation of hands, position relative to fireline, tool displacement, tool stroke rate, and tool head path (5).

Regular workers were observed to assume a body posture primarily using arm and shoulder muscles to power fire tools. In direct contrast, skilled workers were observed using the larger leg and trunk muscles mainly, and the significantly smaller arm and shoulder muscles sparingly. Arm and shoulder muscles are significantly smaller than leg and trunk muscles. Consequently, regular workers were expected to fatigue much more quickly due to the size difference of these

muscles. It was determined that a biomechanical analysis could detail the body posture and tool swing techniques of skilled firefighters primarily using their leg and trunk muscles for grubbing.



Figure 1—Field testing with position/angle motion capture/analysis system.

From these findings, it was recommended that further efforts be directed to investigating optimum user technique in terms of body posture and tool swing techniques of skilled firefighters who use primarily leg and trunk muscles for grubbing. Furthermore, a formal training course for the use of fire hand tools is not available and firefighters receive informal training with varying degrees of proficiency at the local level.

ERGONOMIC CONSIDERATIONS

Ergonomic principles can be used to prevent or minimize injuries in the workplace, specifically in the use of hand tools. Ergonomic concerns, once identified, can be addressed and optimized. Information gathering regarding ergonomic concerns can be obtained by several different methods. These methods include employee lost time injury reports, worker surveys, and general observations as the employee works. Worker compensation costs for ergonomically induced injuries are substantial.

Employee incident and injury records provide important statistically based information regarding ergonomic issues in terms of lost time and injury costs/trends (6). Firefighter lost time/injury analysis and trends have not been conducted for the use of fire hand tools. However, a survey regarding the design and use of standard fire hand tools by IHC's and general observation has been conducted (3,7).

Firefighter comments from this fire tool survey identified low back pain and symptoms of carpal tunnel syndrome as the two most common health areas of concern. This survey also determined that IHC's modify many of the tools they use. Furthermore, minor modifications to gloves were being performed. Some IHC firefighters have reported turning gloves inside out in an attempt to increase grip strength. This action involves exposing the glove seams, thereby increasing glove surface area making contact with the tool handle. Incidents of turning gloves inside out have decreased since these wildland firefighter gloves were redesigned in 1995, with better seam design, improved sizing and shorter welts, or seam edges (8).

Some IHC firefighters have described a desire for a glove with even smaller seams, no seams on the palm, and gloves that extend several inches above the wrist, as compared to the redesigned wildland gloves. There have been reports of some IHC firefighters buying "structure" type gloves using personal funds. These gloves have a rough outside surface, thinner seams, and no seams in the palm, all aspects that increase grip

strength. Also, they typically extend at least 4 inches past the wrist, important in preventing embers, dirt, and debris from getting into the gloves. In addition, some IHC firefighters roughen up the tool handle surface by removing handle varnish to increase the friction value, increasing gripping action. Gripping strength can be increased by exercising with a handspring device. Current research indicates that ergonomic areas of concern should be investigated when workers have designed or modified their own tools or PPE (9).

General observations of firefighters grubbing with standard fire tools and several new hand tool constructions provided direction into a key ergonomic consideration, biomechanics. A wide variance in tool swing technique/motions and body posture associated with the use of fire hand tools was apparent during field testing.

From these findings, project efforts were directed to investigating user technique, in terms of the biomechanics of grubbing motions of skilled firefighters, in an attempt to improve safety and reduce the potential for ergonomically induced injuries, namely carpal tunnel syndrome and low back pain. This study provided an opportunity to capture the experienced firefighter's knowledge and use that knowledge to help train new and less experienced firefighters.

Carpal Tunnel Syndrome

Carpal tunnel syndrome is a type of cumulative trauma disorder associated with repeated, sometimes forceful movements involving the wrist or arm. The anatomy of the wrist is comparable to a narrow tunnel of bones and ligaments, with the median nerve passing through. Sometimes this tunnel becomes "more narrow and pressure is applied to the median nerve, the softest component. This pressure on the median nerve is indicated by the symptoms of tingling, at times painful sensations in the hands. Complaints also include changes in sensation, loss of power or strength with a decrease in the ability to squeeze

or pick up objects with fingers. The carpal tunnel may become more narrow due to: ligaments becoming thicker and sticky due to normal wear and tear from repetitive motion or aging; healed bones from an old fracture protrude into the tunnel; bones getting thicker from arthritis; or fluid retention in tissues, in the carpal tunnel. Because carpal tunnel syndrome is cumulative, workers do not notice damage for months, even years" (9). See figure 2.

The Director of Biomedical and Behavioral Science for the National Institute for Occupational Safety and Health (NIOSH) provided Congressional Testimony regarding health hazard evaluations indicating that job tasks "involving highly repetitive manual acts, or necessitating wrist bending or other stressful wrist postures, are connected with incidents of carpal tunnel syndrome or related problems. Moreover, it is apparent that this hazard is not confined to a single industry or job but occurs in many occupations. The factor common in these jobs is the repetitive use of hand tools (10).

In the same Congressional Testimony, recommendations for "controlling carpal w:nnel syndrome have focused on ways to relieve excessive wrist deviations and arm and hand movements requiring force. Some of NIOSH's recommendations involve redesign of tools or tool handles, to enable the users wrist to maintain a more natural hand position and to ensure better distribution of grip forces during work. Still other remedial approaches include altering the existing method for performing the job task, providing more frequent rest breaks, and rotating workers across jobs. Tool and processes redesign are preferable to administrative means, such as job rotation, as a first means of prevention" (10). Subsequently, it follows that firefighters can reduce the potential for carpal tunnel syndrome by using the best particular work method for each fire tool, frequent rest breaks, rotating tools across firefighters, and holding the tool with a

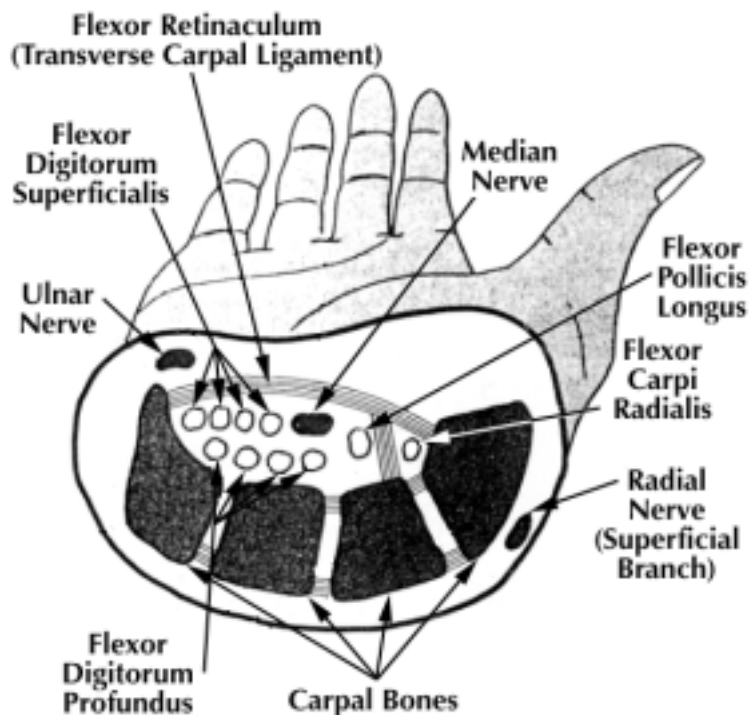


Figure 2—Anatomy of carpal tunnel (10).

more natural hand position with good gripping action. These are especially important for Type II crews who are not typically work hardened as much as Type I IHC crews.

The parameters that best describe body position, tool swing technique and forces associated with repetitive motions related to carpal tunnel syndrome were determined to be the wrist and elbow range of motion, joint angular velocity profiles, peak angular velocities, motion cycle time, tool lift height, tool head path, tool acceleration on impact, position relative to fireline, and tool stroke rate.

Low Back Pain

The exact origin of low back pain is not well understood. There is no strong correlation among weight, height, stature, and the incidence of low back pain (11,12). However, there are reports that indicate that factors such as physical fitness, abdominal muscle strength, trunk muscle

balance, exposure to heavy lifting or vibration, and even cigarette smoking, are positively correlated to episodes of low back pain (11,12). Other personal factors such as fatigue, postural stress, trauma, emotional stresses, degenerative changes, congenital defects, genetic factors, and neurologic dysfunction and body awareness should also be evaluated (13). Research shows a strong correlation between low back injuries and occupations requiring:

- Repetitive or forceful lifting, pushing or pulling
- Repetitive or forceful bending
- Repetitive or forceful twisting
- Awkward postures
- Asymmetrical loading of the spine (e.g., one handed exertions), and
- Exposure to low frequency vibration (14).

Research on low back pain has progressed beyond identifying risk factors to include dynamic and three dimensional modeling to evaluate stress patterns induced during manual lifting; and to determine how to decrease the stresses through varying different load factors or lifting techniques (13).

Varying load factors and lift techniques are best described by the arm reach, weight of the tool, body position, and tool swing technique. The arm reach necessary to lift or lower a tool is an important factor in the amount of moment/load translated to the lower back. This load is comprised of the distance of the tool in the hand to the back muscles, multiplied by the weight of the tool. The longer the arm reach, the longer the moment arm, the greater the load, the greater the incident of low back fatigue, and the greater the incident of low back strain and injury. Consequently, the location of the tool relative to the operator's body is critical in low back strain. The shorter the arm reach the better. Figures 3a and b provide examples of a static two-dimensional biomechanical model, where (M) represents the force produced by the muscle (14).

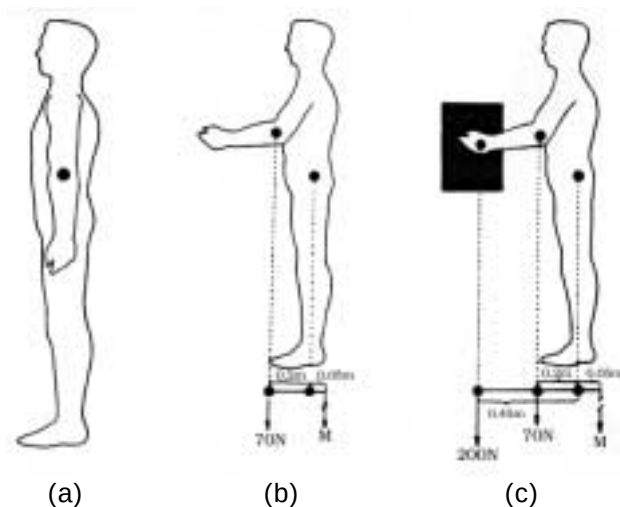


Figure 3a—Force diagram of stresses/moment on low back (14).

Carrying loads by using both hands and by bringing the loads closer to the midline of the body are effective in reducing required musculoskeletal forces (15).

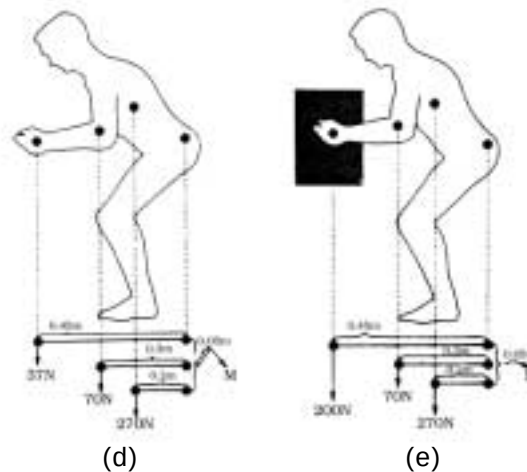


Figure 3b—Force diagram of stresses/moment on low back (14).

The body positions and tool swing techniques that best describe motions and forces from the use of five hand tools, associated with low back strain were determined to be left and right shoulder joint angle profiles, joint angular velocity profiles, peak angular velocities, body posture at maximum tool lift height and tool impact, tool lift height, tool head path, tool acceleration on impact, and position relative to fireline.

ERGONOMIC FACTORS

Grip Strength

Grip strength and physical fitness are important ergonomic factors to consider in evaluating the use of fire hand tools. Grip strength is influenced by several factors, including wrist position, hand tool configuration and the use of gloves. Grip strength is greatest when the wrist is straight (pistol type grip). When the hand moves away from that posture, stress increases on the nerves and tendons entering the hand. When the wrist is bent (right-angle grip) and force applied, cumulative trauma can result. See figure 4 (16).

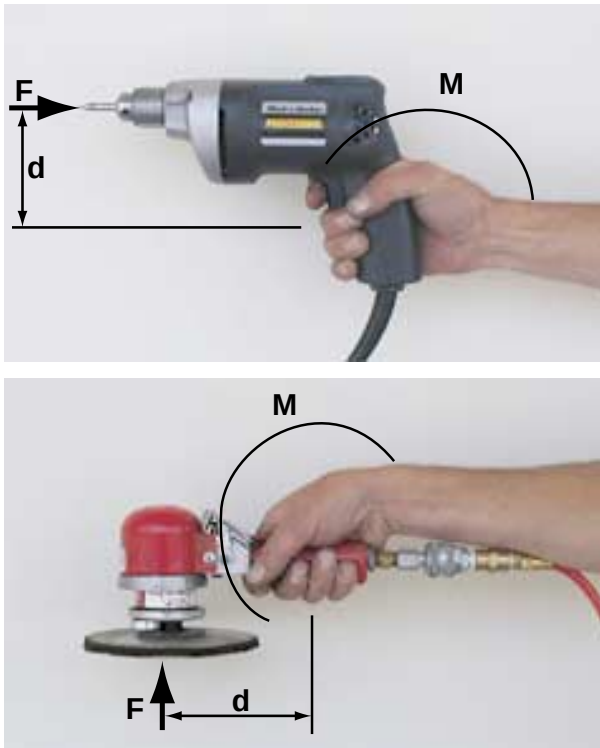


Figure 4—The distance, d , between the location where tool is held in the hand and location where force, F , is exerted; is less for a typical pistol-shaped tool than for a typical right-angle tool (17).

Stress to the wrist increases as the wrist angle increases because the force necessary to grip a right-angle tool is higher than compared to a pistol shaped tool. In addition, there is a greater tendency for a right-angle tool to twist out of the hand than for a pistol type tool. See figure 4 (16).

However, Riley, et al, have shown that, in some cases, gloves increase the force that can be exerted to keep objects from rotating or sliding out of the hand. The effect of gloves on tool force requirements probably depends on whether force is required to actively squeeze the tool or to passively resist the twisting and sliding of the tool (17).

Another factor that influences the amount of power grip strength available is the type of gloves worn. Gloves without seams between the fingers interfere the least with grip force development. Thick gloves with seams can reduce grip strength up to 40 percent.

A loss of grip strength while wearing gloves may lead to negative consequences, including dropping the tool, poorer control of the tool, lower quality of work, and increased fatigue (18).

Fire hand tools are, by design, right-angled tools used in a power grip. Consequently, a high grip strength and gloves with a good fit are important to providing adequate counter forces to right-angle fire hand tools in a power grip. Grip strength can be increased with the use of spring-loaded hand strengthening devices. It is important to wear properly sized gloves. Use standard issue, heavy-duty leather gloves manufactured in accordance with USDA Forest Service Specification 6170-5. Tighten the wrist strap on the gloves for best fit. Replace gloves as soon as needed.

Physical Fitness

A considerable amount of scientific research has been conducted supporting the position that firefighting is one of the most physically and mentally demanding occupations. The levels of muscular and aerobic fitness are critical to firefighter performance and the potential for accidents or injury. Muscular fitness is defined as the level of strength and muscular endurance. Aerobic fitness is the ability or efficiency of the body to take in and deliver oxygen to the muscles during arduous activity at a sustainable rate over the workday. A minimum performance standard based on physical requirements of the job is crucial to safety.

Studies of firefighting and other field tasks confirm the link between fitness and work performance. Fit workers perform better in the heat. They acclimate faster and work with a lower heart rate and body temperature. They lose acclimatization slower and regain it faster. Fit workers cope better with and recover from adverse firefighting conditions like long shifts and reduced sleep and rest. The physically fit employee misses fewer days of work because of illness or injury.

Even fit, well-rested firefighters will tire too quickly when they work inefficiently. Inefficiency wastes energy. New workers can be inefficient until they get instruction and practice in hand tool use. Veteran firefighters are inefficient when saddled with the wrong fire tools for the job. The right tool can minimize fatigue and energy expenditure.

Fitness is the most important factor in predicting work capacity. Work capacity is the ability to accomplish production goals without undue fatigue, and without becoming a safety hazard to yourself or coworkers. Many Federal and State agencies have used the step test to predict aerobic fitness. Fitness can't be rushed and is a gradual process. Depending on the present fitness, a firefighter may need 6 weeks or more of exercise to shape up. That is why prudent workers get into shape before the season begins. They do not work themselves into condition on the fireline (19). Achieving and maintaining fitness and work capacity are well described in the National Wildfire Coordinating Group publication "Fitness and Work Capacity" (20).

Work capacity is the best indicator of the physical requirements of wildland firefighting. A precise method to measure work capacity is important to safety, by the way of setting a minimum physical performance standard. Currently, the most precise method of determining work capacity is the pack test. Transitioning the pack test to replace the step test as an indicator of work capacity is in progress.

BIOMECHANICAL TEST PARAMETERS

Biomechanical parameters associated with carpal tunnel syndrome, low back pain, and related problems in wildland firefighters were determined. Body position and tool swing technique were best described in terms of the use of leg and trunk muscles, arm and shoulder muscles, bendover angle, tool stroke rate, tool lift height, distance the hands are separated when using the tool, position of feet relative to the fireline, and arm reach and shoulder angle. These biomechanical test parameters are left and right shoulder joint angle profiles, wrist range of motion, joint angular velocity profiles, peak angular velocities, body posture at maximum tool lift height and tool impact, motion cycle time, tool lift height, tool head path, tool acceleration on impact, position relative to fireline, and tool stroke rate. Field testing was developed around these parameters.

The original fire tool experimental design matrix developed by SDTDC for a series of successive studies was again utilized, to facilitate the experimental protocol process and data collection efforts. This design matrix is included as appendix B. A biomechanics design matrix to evaluate human/tool kinematics for field testing was developed and followed. This biomechanics test matrix is included in appendix C.

TEST PROCEDURE AND INSTRUMENTATION

Twenty-two firefighters grubbed light fuels to bare soil consisting of decomposed granite at a site with minimal slope using three test tools, the standard and Super Pulaskis and the Combi tool.

A magnetic transmitter/receiver system was used to collect high-speed dynamic data. This system, manufactured by Skill Technologies, Inc, model 6D Research, serial number 82451, uses low frequency magnetic technology to track sensors placed within a magnetic field created by a source. Firefighters were outfitted with

biomechanical sensing equipment, consisting of a transmitter and eight position/angle sensors mounted on seven designated body segments and the tool handle. These eight sensors were cabled to a computer with software capable of recording translational and rotational movement on a rapid basis at 30 hertz. These multiple measurements were taken to provide improved statistics and increased accuracy in biomechanical measurements.

This magnetic sensor system was initially calibrated in order to determine the exact position and orientation of each body sensor. Kinematics were derived from position data, (x, y, z) to include linear and angular velocity, linear and angular acceleration. Tool head position data were obtained, and velocity and acceleration values were derived.

The heart rate was used as a physiological indicator of energy expenditure and was continuously monitored. The heart rate monitor was manufactured by Polaris Inc., model Pulsar II, serial number 431047. In a previous study test workers, grubbing at a rate for indirect line, had a heart rate of 140 to 150 beats per minute. Monitoring apparatus consisted of a transmitter positioned over the lower chest and a receiver taped to the hard hat (3). See figure 5.



Figure 5—Heart rate and monitoring apparatus.

Test workers completed a preference rating of hand tools based on subjective responses/opinions on completion of biomechanical testing. This rating is included as appendix D. A detailed description of the test procedure may be found in the “USDA Fire Tool Ergonomics Testing of Human Kinematics” test plan April 1997 and August 1998 (7).

Test Tools

The fire hand tools tested were the standard Pulaski, the Super Pulaski, and the Combi tool. These tools are shown in figure 6. Physical characteristics are indicated in table 1. Tool selection criteria were based on information extracted from IHC respondents to the aforementioned



Figure 6—Test tools of the Combi tool, standard Pulaski, and Super Pulaski.

Table 1—Test Tool Configurations

Tool Number	Tool Head Type	Handle Length Inches	Handle Material	Weight Pounds	Hoe Width Inches	Weight/Width Pounds/inch
1	Standard Pulaski	34.5	Wood	5.4	3.0	1.6
2	Super Pulaski	34.5	Wood	6.9	6.8	1.0
3	Combi Tool	40.0	Wood	4.6	4.0	1.2

fire tool survey (3). The Combi tool was included as the reference grubbing tool for comparison based on high productivity rates determined by the MTDC tool study in 1988. Each of the test tools was sharpened, as appropriate, to a standard sharpness and angle for scraping prior to use. The tools were archived as reference tools for further testing.

The standard Pulaski and Combi tool are manufactured in accordance with the minimum requirements of Forest Service Specifications 5100-355 and 5100-325 respectively. The Super Pulaski used in this test was a field modification consisting of a standard Pulaski with an additional standard Pulaski hoe blade, cut into two pieces and welded onto the basic hoe, half on either side.

There are several variations of the Super Pulaski currently being used in the field by IHC firefighters. Their design ranges from the welded double hoe used in this test, to a more refined design of a wide hoe blade fabricated as one piece via a sand casting, with a decreased weight, smaller hoe blade, and no weld lines present. Based on a comparative analysis of the field modifications and commercially available Super Pulaski configurations, the heaviest double welded hoe design of the Super Pulaski was selected due to the expected severe application.

Preparation for Testing

Test workers were outfitted in full PPE and gear. Fire shelters were removed from the carrying case and replaced with practice shelters, because the fire shelters contain a ferric-based metal that interfered with the magnetic motion sensor system. Two full water canteens were included. A fully equipped test worker is shown in figure 7.



Figure 7—A test worker in full gear and PPE.

Each test worker was fully instrumented prior to testing. In addition, each worker was briefed on what was to be accomplished during the test procedure. The instructions on how testing was conducted were the same for each test worker.

The test site consisted of minimal slope, decomposed granite and light fuels. Heavier roots were removed prior to testing to maintain a light uniform fuel. Removal was minimal. A fireline quality of grubbing to bare soil was monitored and standardized as much as practicable.

The heart rate was used as a physiological indicator of energy expenditure. Consequently, the test workers in this study were coached to speed up or slow down grubbing in relation to the desired heart rate. Monitoring apparatus consisted of a transmitter strapped around the lower chest and positioned without restricting normal upper body movement. The heart rate receiver was taped to the top of the hard hat in a position readily visible to the test engineer, when the worker was in the grubbing position.

The biomechanics sensor system was configured to determine left and right shoulder joint angle profiles, wrist range of motion, joint angular velocity profiles, peak angular velocities, body posture at maximum tool lift height and tool impact, motion cycle time, tool lift height, tool head path, tool acceleration on impact, position relative to fireline and tool stroke rate.

Test workers were instrumented with seven sensors immediately prior to testing. An eighth sensor was mounted on the handle of the tool to be tested, near the head. The tool head consisted of a ferrous-based metal and interfered with the magnetic motion sensor system. Consequently, the tool sensor was positioned approximately 4 inches down the handle. This dimension for tool sensor placement on the handle was used as a correction for the tool head data. See figure 8.



Figure 8—Position/angle sensor mounted on the tool head.

Test workers had a 3-minute warm-up period of grubbing with each test tool, for a total of approximately 5 minutes of grubbing per tool.

Detailed Test Method

Instrumented test workers warmed-up for 3 minutes by digging simulated fire line. They were coached to either increase or slow the rate of grubbing to bring the heart rate to 130 to 140 beats per minute. After 3 minutes, the worker moved to the test course and was positioned in front of the system receiver for system calibration. Calibration took 10 to 15 seconds.

The test worker was instructed to begin grubbing in the test course, making a trench about 12-inches wide and 2-inches deep. Grubbing techniques were monitored and standardized as much as practicable. Grubbing was performed within a range of 12 feet from the magnetic system transmitter. See figure 9.



Figure 9—Test worker grubbing in the test course.

The Project Leader signaled the test crew to begin gathering data. Data were collected for a total of 25 strikes or more.

After data collection was completed on a tool, the test worker progressed to the next tool. Tool changeover and tool sensor application took 10 to 15 seconds. The test worker was again positioned in front of the system transmitter for calibration before the use of each tool.

Position/angle sensor data were collected via a computer. The magnetic sensors had a sampling rate of 30 Hz or 30 cycles per second. Sensor data were stored in an ASCII file format, tab delimited and were imported into an Excel spreadsheet for analysis. Testing was videotaped for project documentation. The derived kinematic data were stored on disk for analysis.

Determination of Skilled and Regular Firefighters

Tool testing was documented with technical videotape. This videotape was viewed and the Dalton IHC Superintendent and Assistant Superintendent evaluated skill level. Based on this evaluation the workers/firefighters were categorically grouped, based on skill level in terms of regular versus skilled firefighter. The top six regular and skilled firefighters were selected. Gender was mixed for both skill categories.

DETAILED DATA ANALYSIS BY TOOL

As a result of the continuous data collection process, multiple cycles of the grubbing motion were provided for each tool and test worker. As a result, the average motion over a number of cycles, 25 or more, for each worker and tool were determined. The average and standard deviations for all designated motions, for all three tools, for both regular and skilled groups, were determined. Variables of interest were calculated and a comparative analysis was performed between the group averages and standard deviations for each tool. Comparison parameters were:

- Work cycle time (tool stroke rate)
- Tool lift height
- Tool impact acceleration (tool impact force or gs)
- Tool head path
- Hand separation
- Posture at maximum tool lift height
- Posture at tool strike/impact acceleration

-
- Range of motion, for all joints
 - Peak angular velocities, for all joints
 - Joint angle profiles, for left and right shoulder for internal/external rotation, adduction/abduction, and flexion/extension.
 - Joint angle profiles, for left and right elbow for pronation/supination, adduction/abduction, and flexion/extension.
 - Joint angle profiles, for left and right wrist for internal/external rotation, ulnar/radial deviation, and flexion/extension.
 - Joint angular velocity profiles, for left and right shoulder for internal/external rotation, adduction/abduction and, flexion/extension.
 - Joint angular velocity profiles, for left and right elbow for pronation/supination, adduction/abduction, and flexion/extension
 - Joint angular velocity profiles, for left and right wrist for internal/external rotation, ulnar/radial deviation, and flexion/extension.

Data analysis of the most pertinent graphs follows. All other associated graphs and tables are provided in appendix E.

Standard Pulaski

An examination of joint angle profiles for the biomechanics associated with the use of the standard Pulaski indicates that hand and shoulder position vary significantly between regular and skilled workers/firefighters. Regular workers performed the first half of the motions with respect to shoulder and hand position similar to that of a skilled worker. However, regular workers draw the second half of the motion out and perform it much more slowly. See figures 10 and 11. Hand separation profiles are very similar between regular and skilled workers. The hand separation for regular workers on the average was 15 inches, and 16 inches for skilled workers. No obvious differences are evident in the elbow

and wrist joint angle profiles. Angular velocity peaks did not seem to differ significantly between regular and skilled workers. See table F1.

Significant differences in cycle duration, tool impact force, and lift height were observed between regular and skilled workers with the use of the standard Pulaski. Regular workers had an average cycle duration of 1.1 seconds, 55 tool strikes per minute, tool impact force of 4.5 gs, and lift height of 32 inches. Skilled workers had an average cycle duration of 0.8 seconds, 75 tool strikes per minute, tool impact force of 2.7 gs, and lift height of 20 inches. Skilled workers are 36 percent more productive as determined by tool strike based on the assumption that the grubbing effectiveness is the same for skilled and regular workers. This is probably not true and gives a benefit of error in the favor of the regular worker.

Tool head acceleration is best described in terms of tool impact and G forces. The G force is a force of acceleration that pulls on the tool head. The force of gravity on Earth is used as a baseline for measuring this force of acceleration. Gs are directly related to the weight of the tool. As the firefighter pulls more gs, the weight of the tool head or G force increases correspondingly. The 5.4-pound Pulaski has 1 g when motionless, for a G force of 5.4 pounds. However, the same 5.4-pound standard Pulaski moving with 4.5 gs will weigh 24 pounds when used by regular firefighters. Skilled firefighters typically generate around 2.7 gs or 15 pounds G force on impact. The lower the G force on impact the better.

Regular workers performed two motion cycles for every three completed by a skilled worker. See figures 12, 13, and 14. Skilled workers can complete 75 tool strikes for every 55 by a regular worker, or are 36 percent more productive. Using standard hand crew

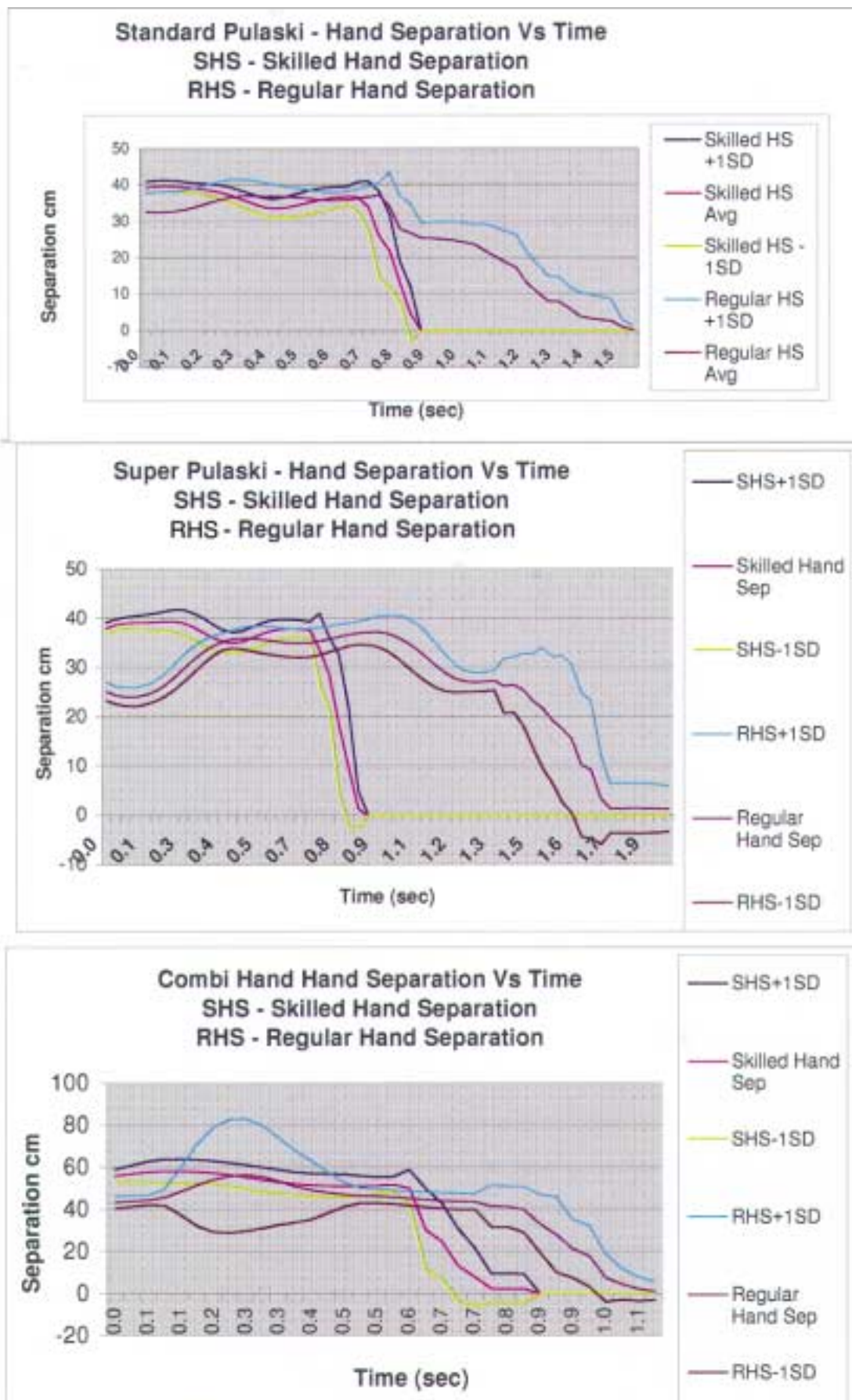


Figure 10—Hand separation, regular workers draw the second half of the motion out.

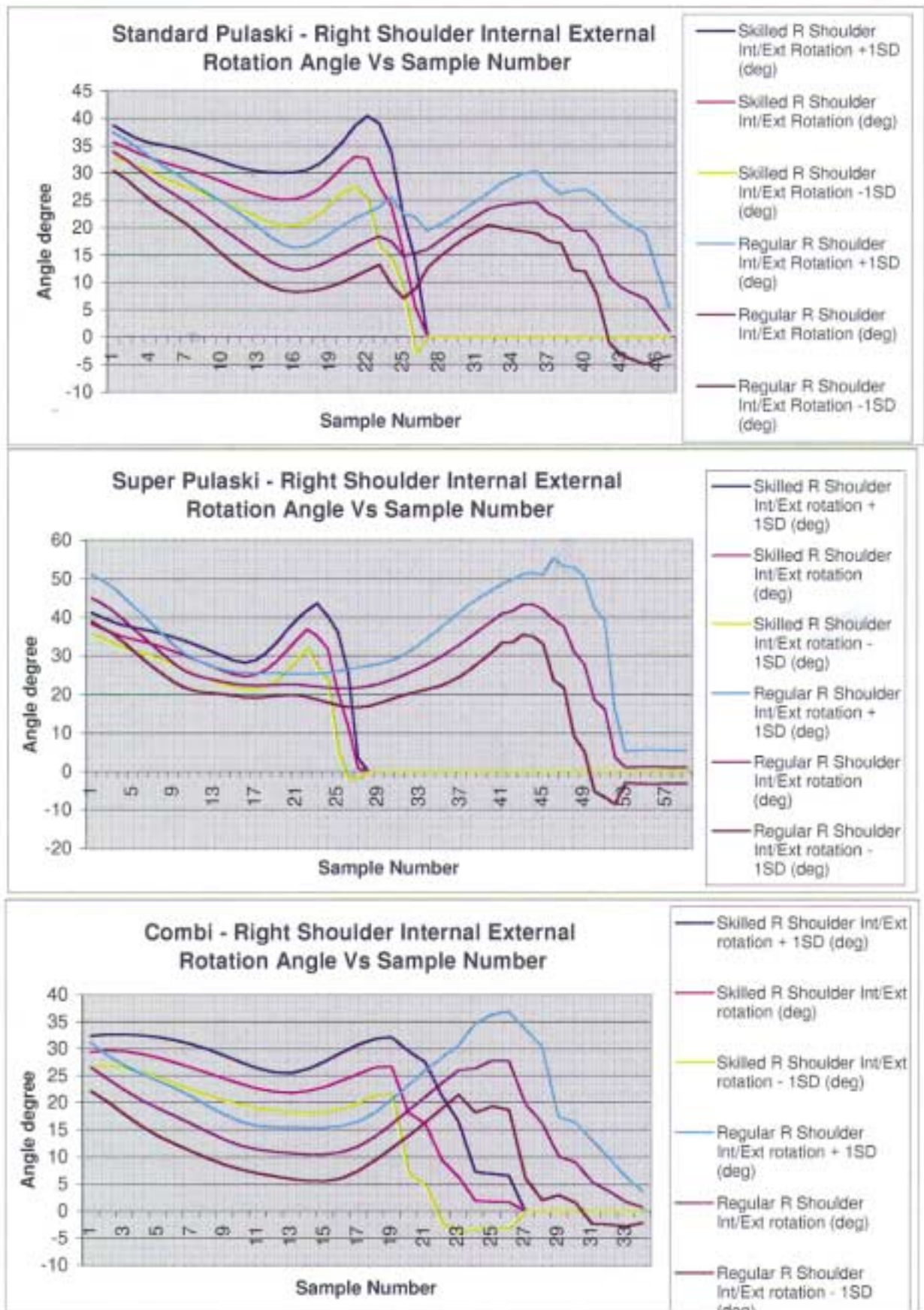


Figure 11—Shoulder position, regular workers draw the second half of the motion out.

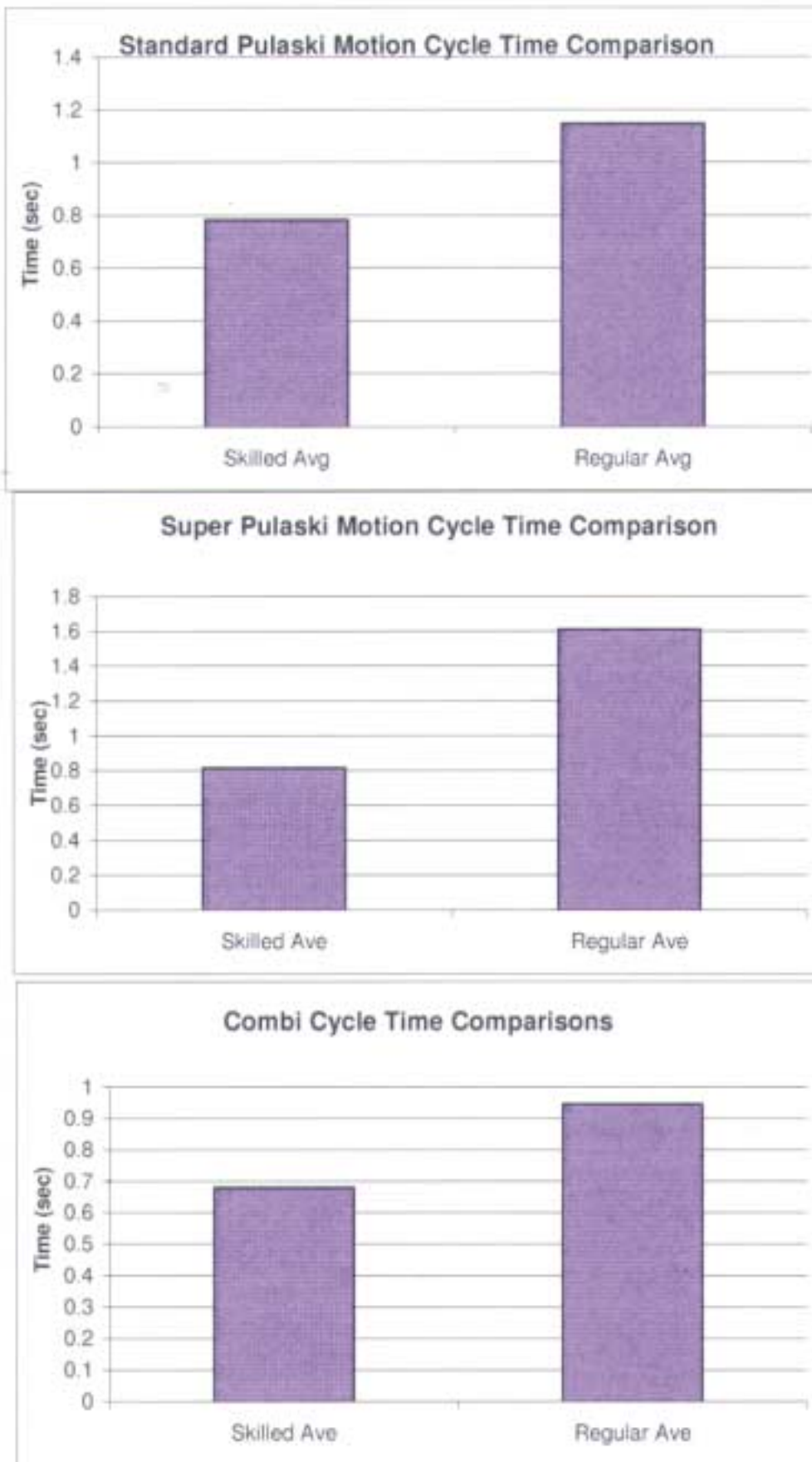


Figure 12—Work cycle duration.

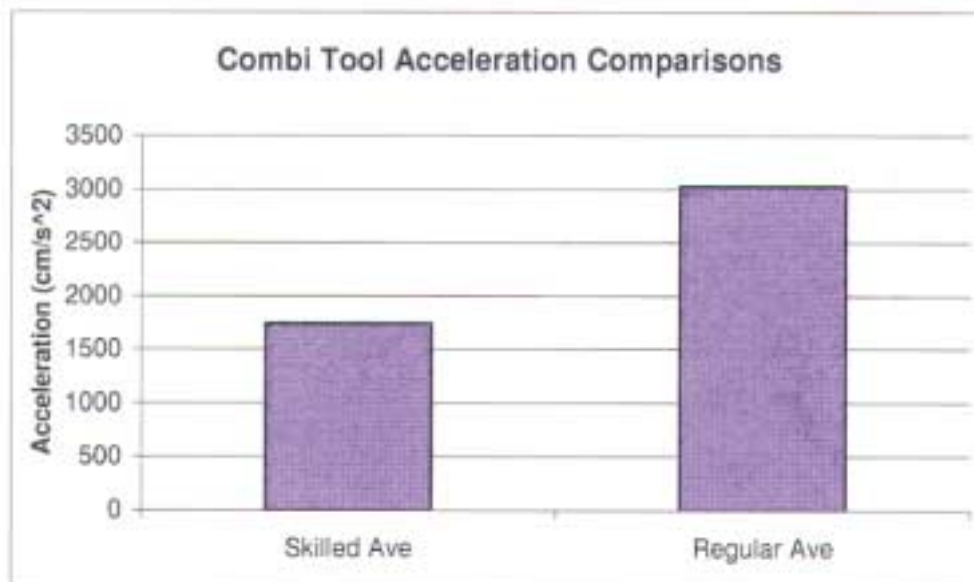
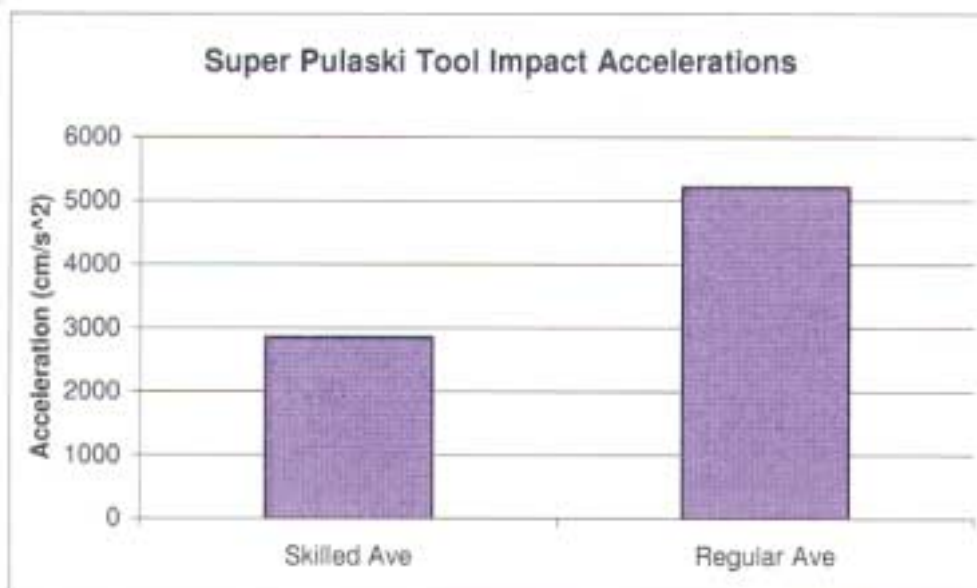
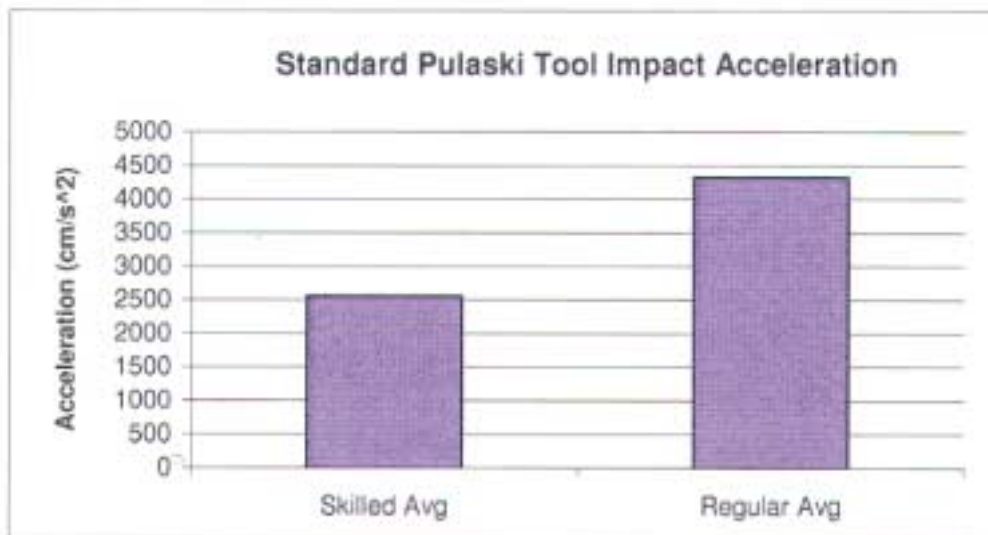


Figure 13—Tool impact force.

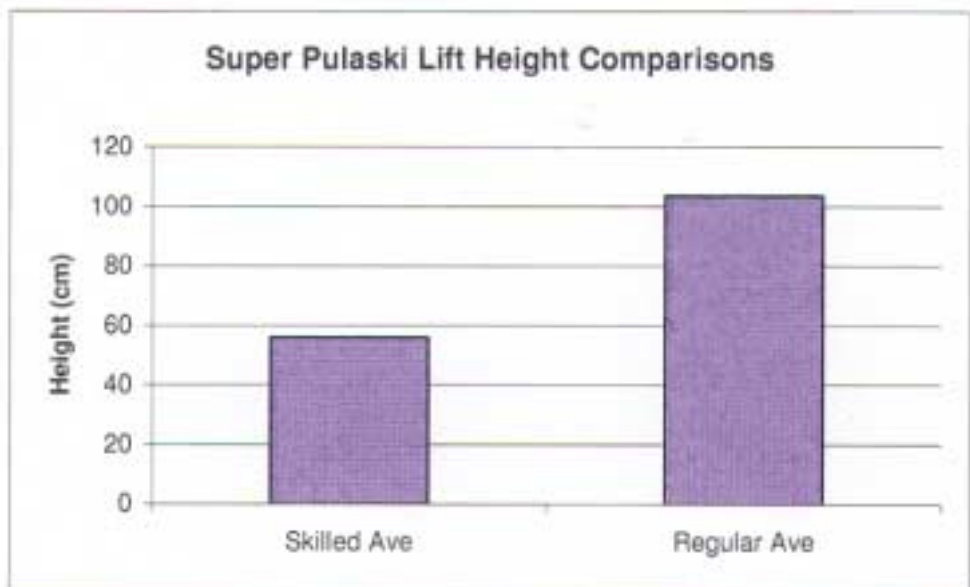
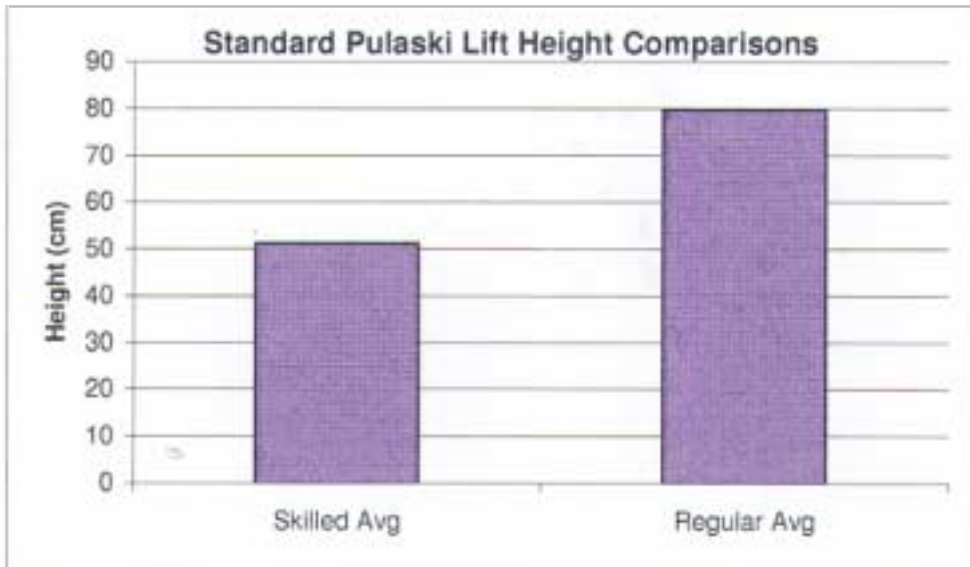


Figure 14—Tool lift height.

production rates for medium brush for a line width of 6 feet, a crewmember can typically average 30 feet of line per hour and a 15-person crew can build approximately 450 feet per hour. An assumption can be made that half of the crew are skilled and the other half are regular workers. A 36 percent increase in productivity can increase line by 68 feet per hour if the whole crew was trained to the skilled level. That is comparable to having 2 people added to a 15-person crew. Again, this is based on the assumption that half the crew is already skilled.

The standard Pulaski has a 3-inch hoe blade. The regular worker with 55 strikes per minute can strike/grub 165 inches per minute. The skilled worker with 75 strikes per minute can strike/grub 225 inches per minute.

In addition, because a regular worker elevates the tool head 50 percent higher than a skilled worker, a regular worker expends the same amount of energy in two cycles as is expended by a skilled worker in three cycles, simply by lifting the tool head higher. Furthermore, a regular worker impacts the tool head with nearly twice the force used by a skilled worker.

Body posture at maximum tool height and tool strike with the use of the standard Pulaski was examined. Positional differences greater than one standard deviation indicate significant areas for improvement in regular workers motion.

Body posture at maximum height the standard Pulaski is lifted is best described by the right and left shoulder angles, right hand reach, and left arm twist. These biomechanical parameters are the angles of right shoulder flexion/extension, left shoulder flexion/extension and adduction/abduction, right elbow flexion/extension, and left elbow pronation/supination. See table F2. For this posture, with one exception, the variability in the key angles about the average posture was comparable, 2 to 5 degrees, for both regular and

skilled workers. However, left elbow adduction/abduction variation was nearly three times greater, around ± 10 degrees in regular workers as compared to skilled; even though their average position was similar, minus 31 degrees in regular workers and minus 35 degrees in skilled workers. See table F2.

Body posture at tool strike shows an increased number of angles indicating differences in angles similar to those noted for posture at maximum tool height. The most significant of these differences are in the right and left shoulder flexion/extension and adduction/abduction angles. Other angles of interest are both wrists and left elbow positions. See table F3. An examination of the individual angle ranges of motion indicates a wide variance between range of motions (ROM) between regular and skilled firefighters, especially in left and right shoulder. See table F4. This is easily observed as regular workers use arm and shoulder muscles to power the tools. In direct contrast, skilled workers are observed to use leg and trunk muscles mainly and arm and shoulder muscles sparingly with the use of the standard Pulaski.

It is clearly evident from the examinations of body posture at maximum tool height and tool strike, and ROM, that shoulder position is important in determining the skill level of a worker using a standard Pulaski.

Key points determined in this kinematic analysis of the use of the standard Pulaski are:

- Regular workers perform the first half of shoulder and hand separation motions similar to that of a skilled worker, but draw out the second half of the motion and perform it much more slowly.
- Regular workers perform two motion cycles for every three completed by a skilled worker.
- Regular workers impact the tool head with nearly twice the force used by skilled workers.
- Regular workers elevate the tool head 50 percent higher than a skilled worker.

-
- Regular workers expend the same amount of energy in two cycles that is expended by skilled workers in three cycles, simply by lifting the tool head higher.
 - Shoulder position is important in determining the skill level of a worker using a standard Pulaski.
 - Regular workers use arm and shoulder muscles to grub. Skilled workers use leg and trunk muscles. Arm and shoulder muscles are significantly smaller than leg and trunk muscles and fatigue quicker.
 - Regular workers using the standard Pulaski with a 3-inch hoe blade, and 55 strikes per minute can strike/grub 165 inches per minute. Skilled workers with 75 strikes per minute can strike/grub 225 inches per minute.

Super Pulaski

An examination of the joint angle profiles for the biomechanics associated with the use of the Super Pulaski reveal patterns similar to the standard Pulaski. However, these differences are more pronounced and distributed among a greater number of the joints. The right shoulder motions for regular and skilled workers follow similar patterns, with the regular worker drawing the motion out over an even longer duration. See figure 11. The elbow pattern differences are the same as that for the right shoulder. See figures 11 and 15. The left shoulder profiles show that a greater range of motion is employed by regular workers for the left shoulder adduction/abduction and flexion/extension angles. See figures 16 and 17.

The wrist angle and velocity profiles with the use of the Super Pulaski are quite interesting. Wrist angles are almost unchanged though the complete tool swing by the regular worker as compared to a skilled worker. See figures 18, 19, 20, and 21. In general, peak angular velocities are higher for skilled workers. See table F1. With

respect to separation of the hands, the regular worker draws their hands together more gradually than a skilled worker. A skilled worker draws their hands together very quickly, almost in a snapping action. Hand separation at the beginning of the up-stroke for regular workers is 10 inches and 16 inches for skilled workers. During up-stroke, regular workers quickly widen hand separation from 10 inches to 15 inches, while skilled workers maintain a constant hand separation of 16 inches until the end of up-stroke, when they snap their hands together quickly early in the down-stroke phase. See figure 10.

As with the standard Pulaski, the use of the Super Pulaski provided pronounced differences in grubbing cycle time, tool impact force, and lift height. In each of these three parameters, the mean value for regular workers was nearly twice that of the skilled worker. Regular workers had an average cycle duration of 1.6 seconds, 40 strikes per minute, tool impact force of 5.3 gs and lift height of 41 inches. Skilled workers had an average cycle duration of 0.8 seconds, 75 strikes per minute, tool impact force of 2.9 gs and lift height of 23 inches. This means a skilled worker can perform two cycles to every one performed by the regular person for a given time duration and energy expenditure. See figures 12, 13, and 14.

Skilled workers can complete 75 tool strikes for every 40 by a regular worker, or are 88 percent more productive. Using the same standard hand crew production rates for medium brush for a line width of 6 feet, as described with the standard Pulaski. An 88 percent increase in productivity can increase line by 136 feet per hour if the whole crew was trained to the skilled level. That is comparable to having 4 people added to a 15-person crew. Again, this is based on the assumption that half the crew is already skilled. However, previous fire tool studies have proven that the increased energy cost far out weighs any production gain.

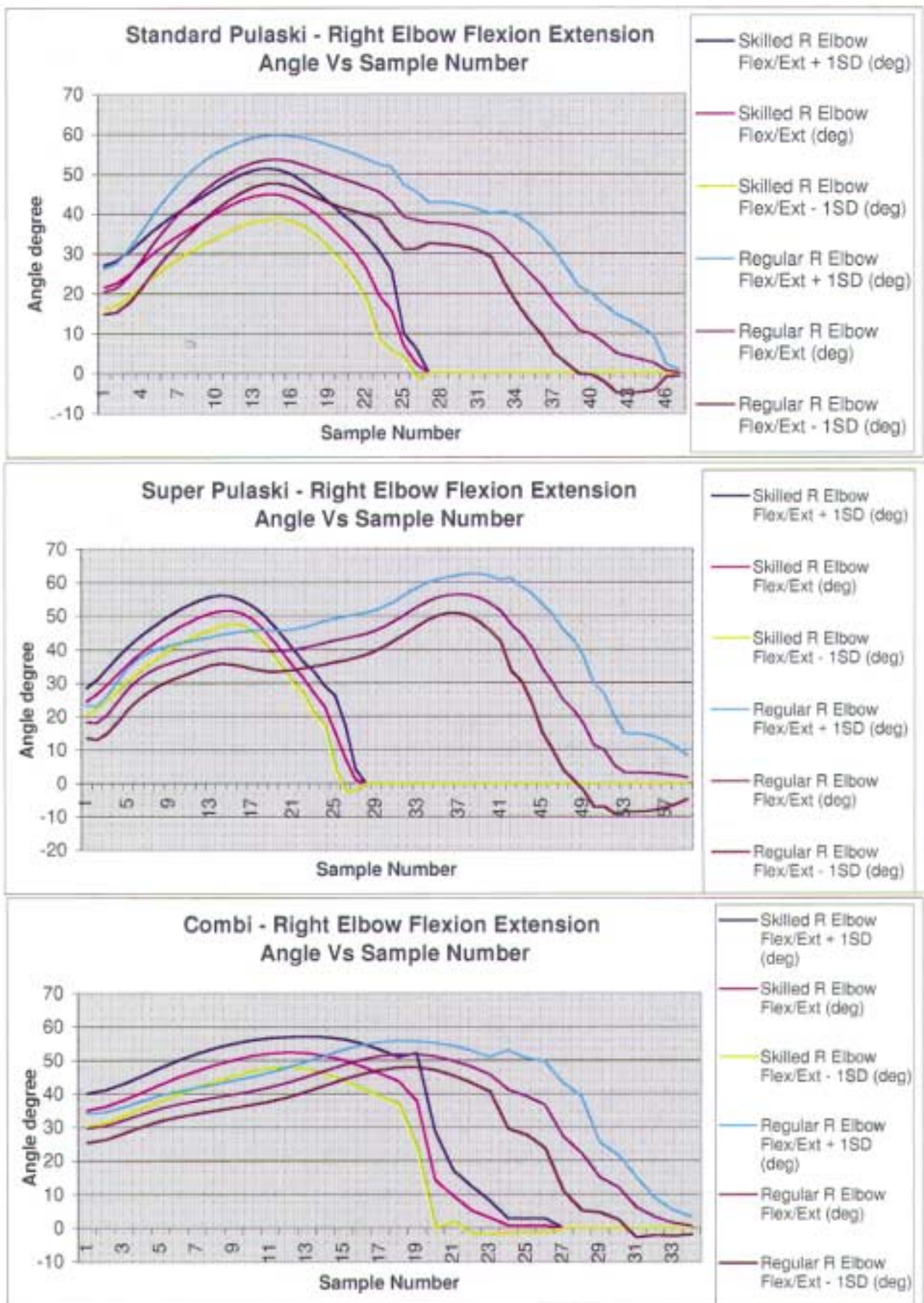


Figure 15—Right elbow flexion/extension angle.

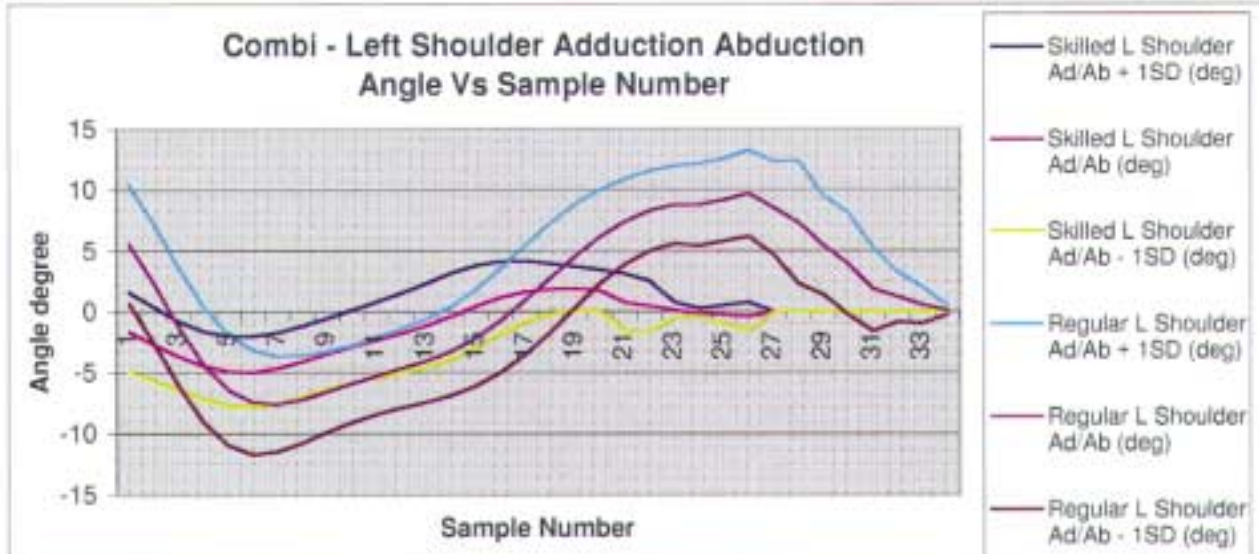
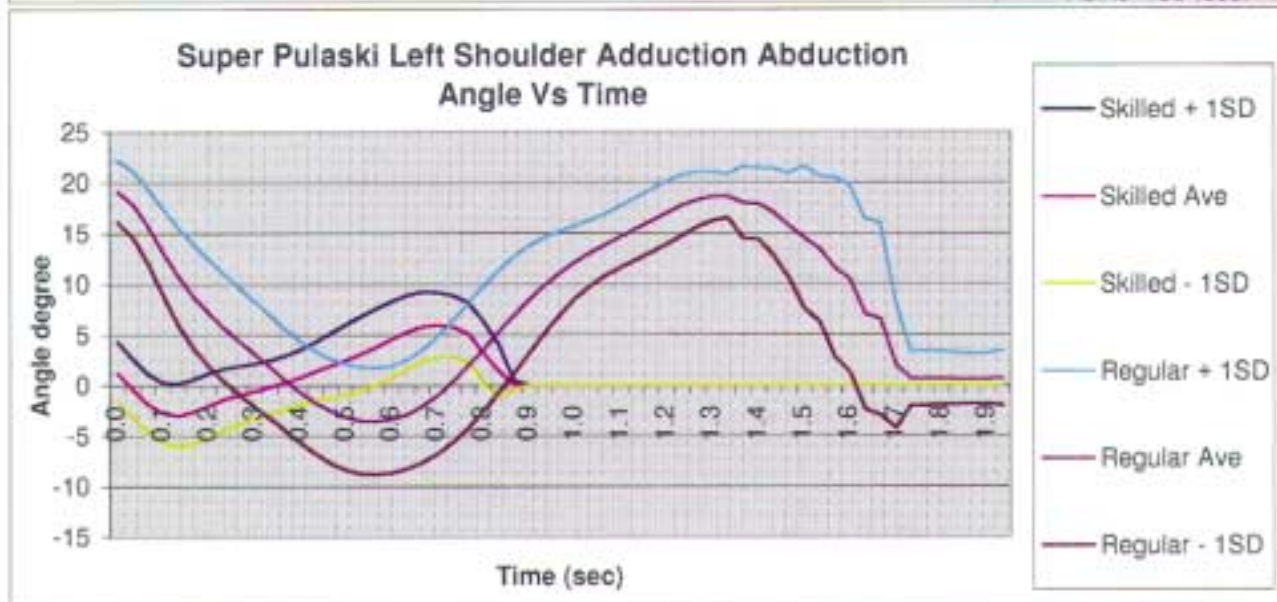


Figure 16—Left shoulder adduction/abduction angle.

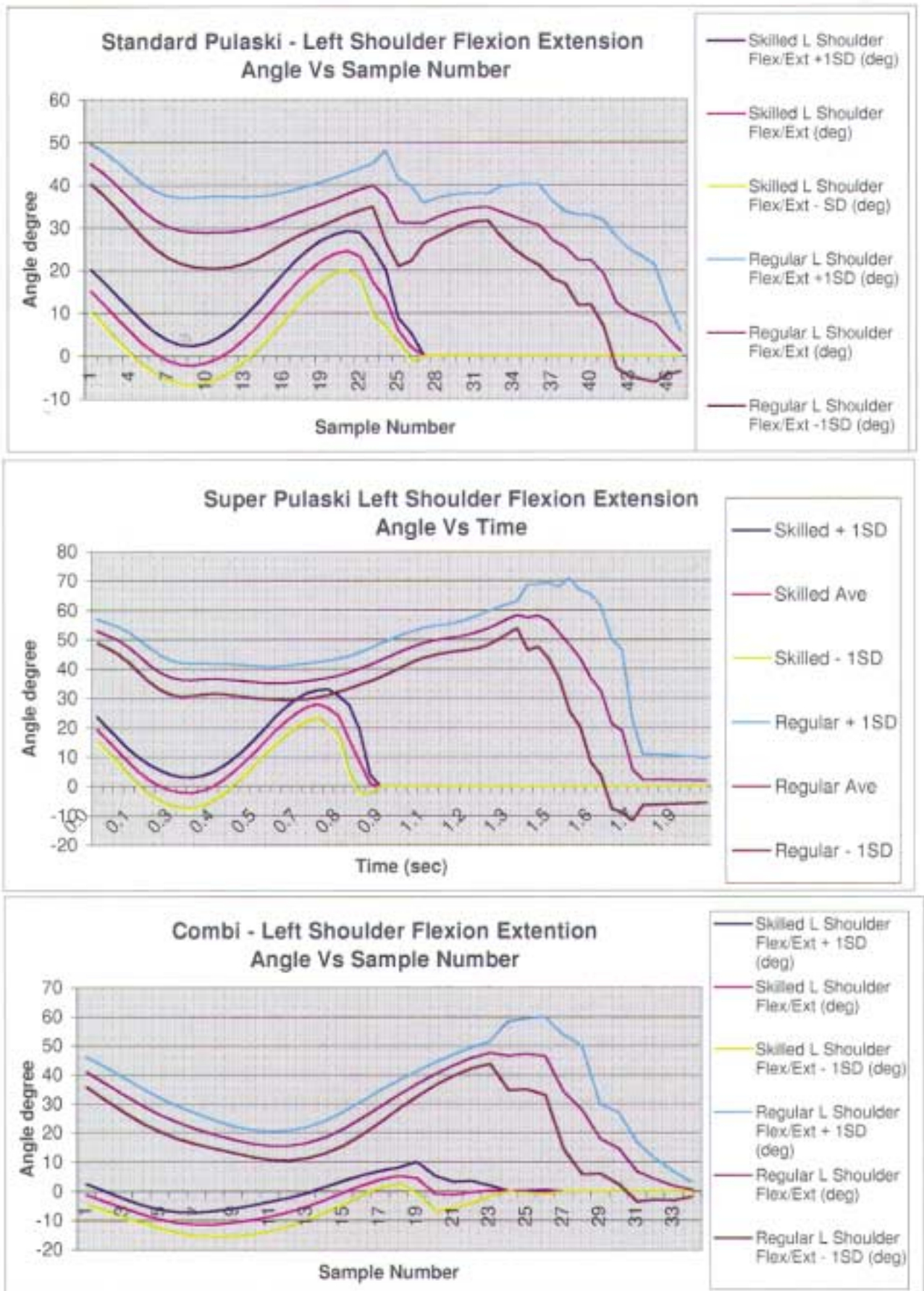


Figure 17—Left shoulder flexion/extension angle.

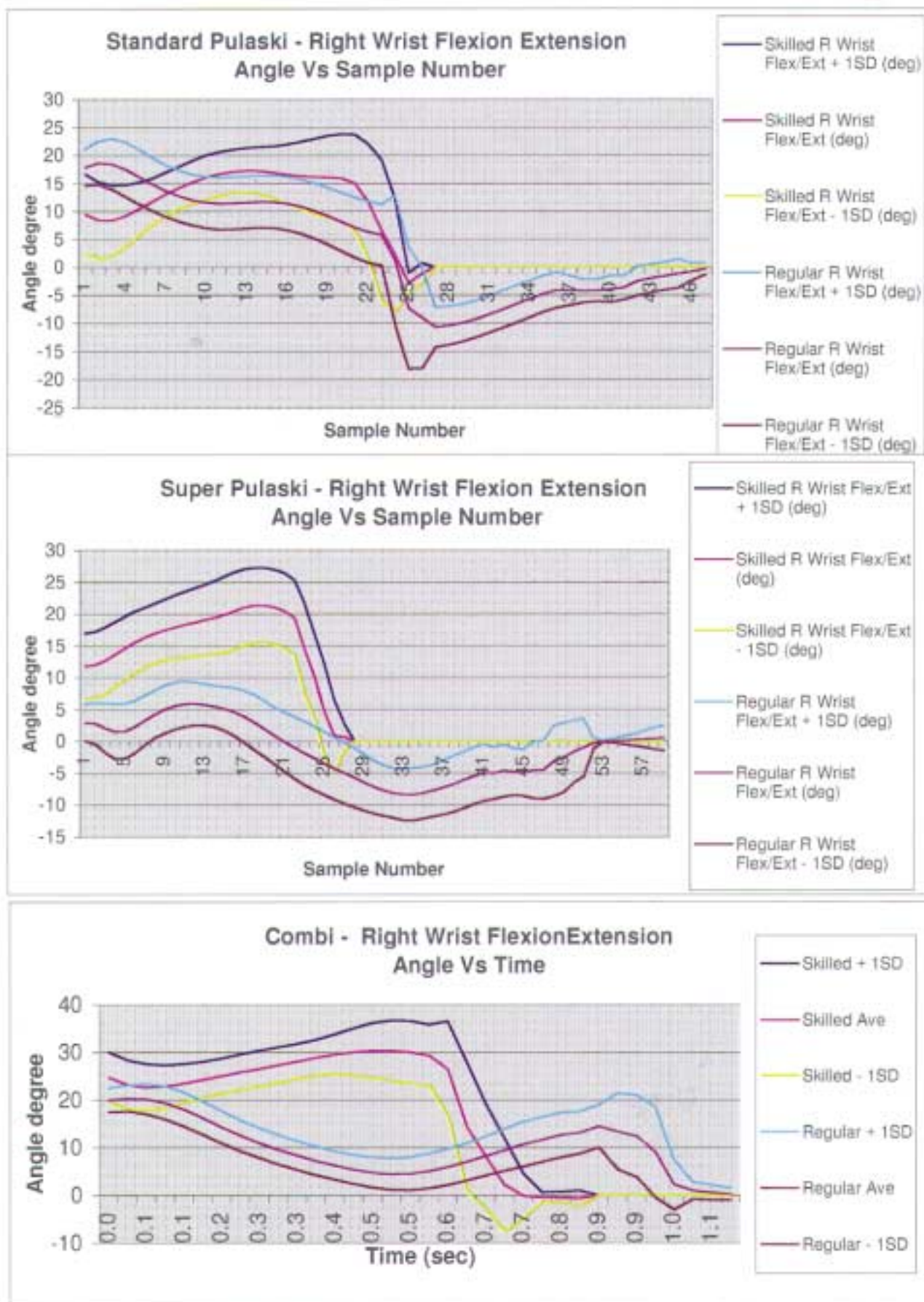


Figure 18—Right wrist flexion/extension angle.

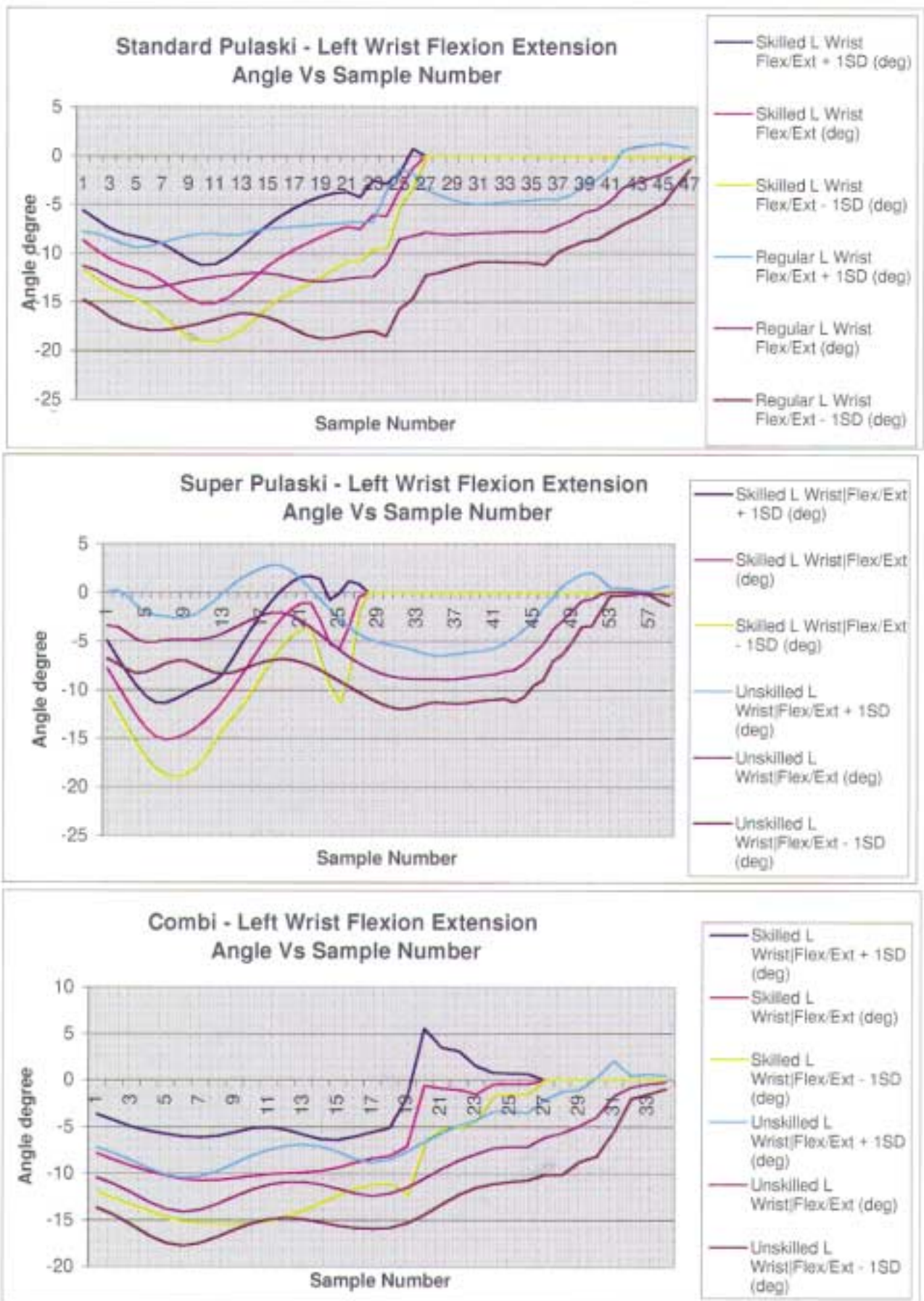


Figure 19—Right wrist flexion/extension angular velocity.

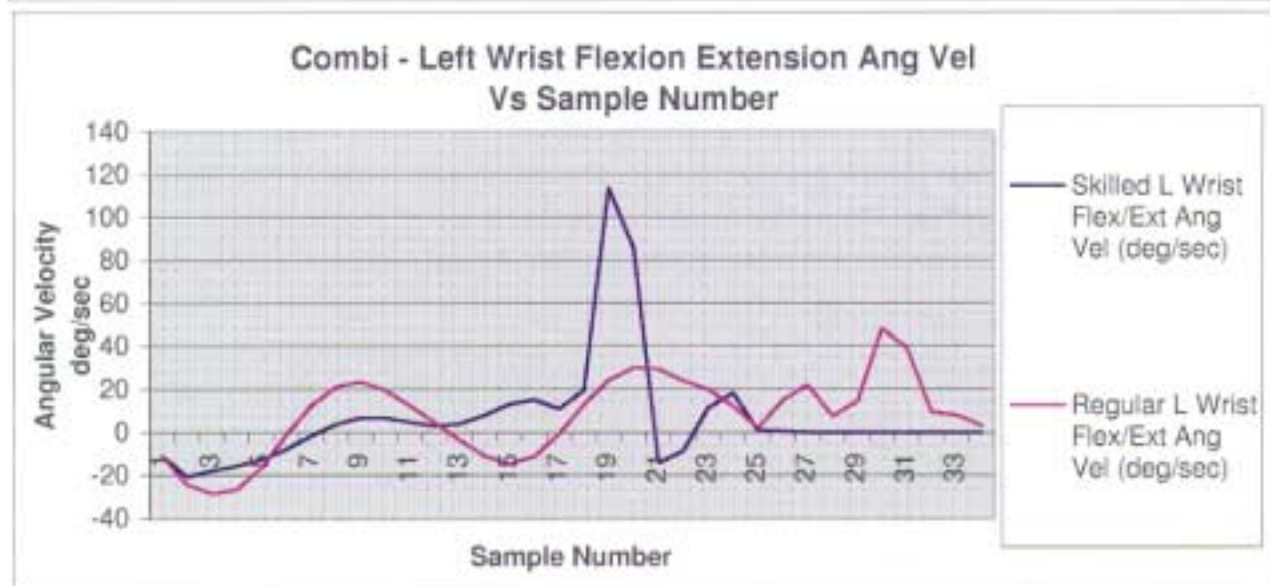
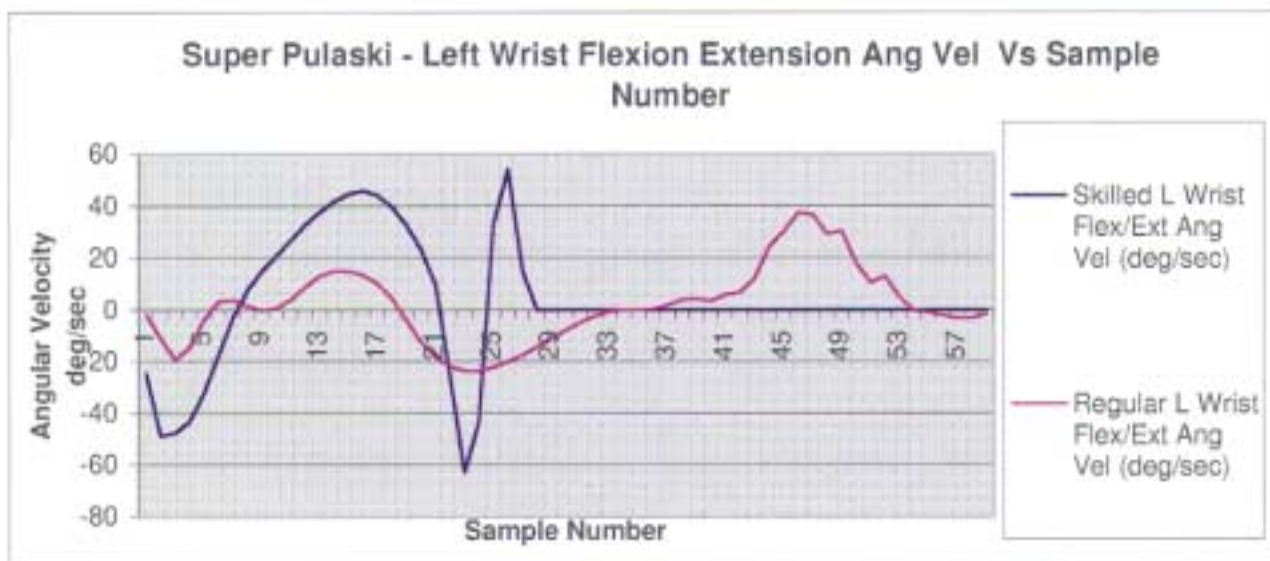
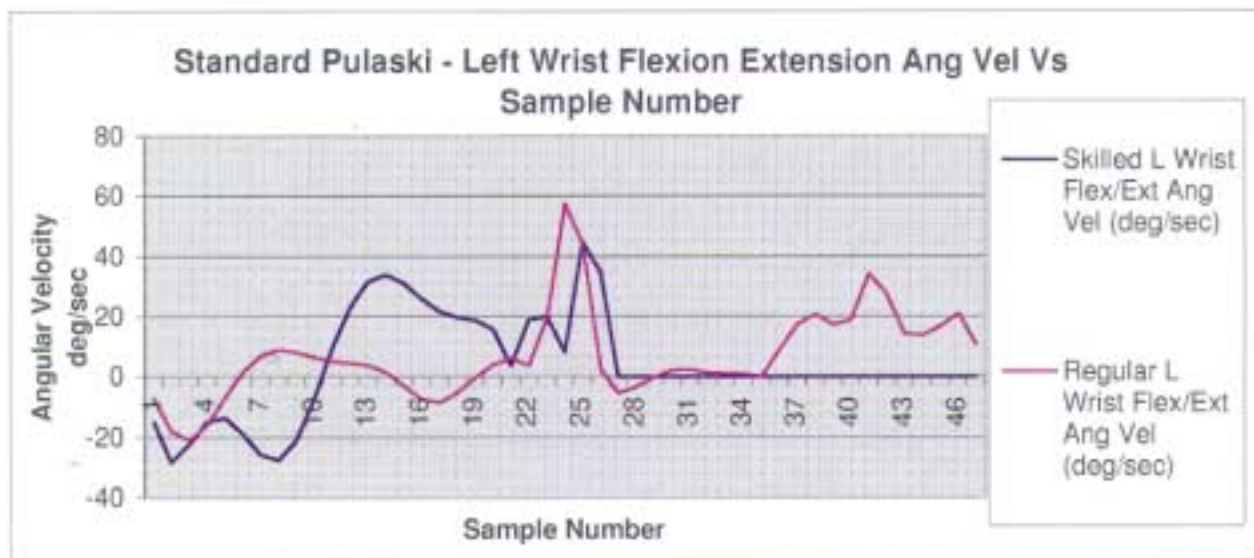


Figure 20—Left wrist flexion/extension angle.

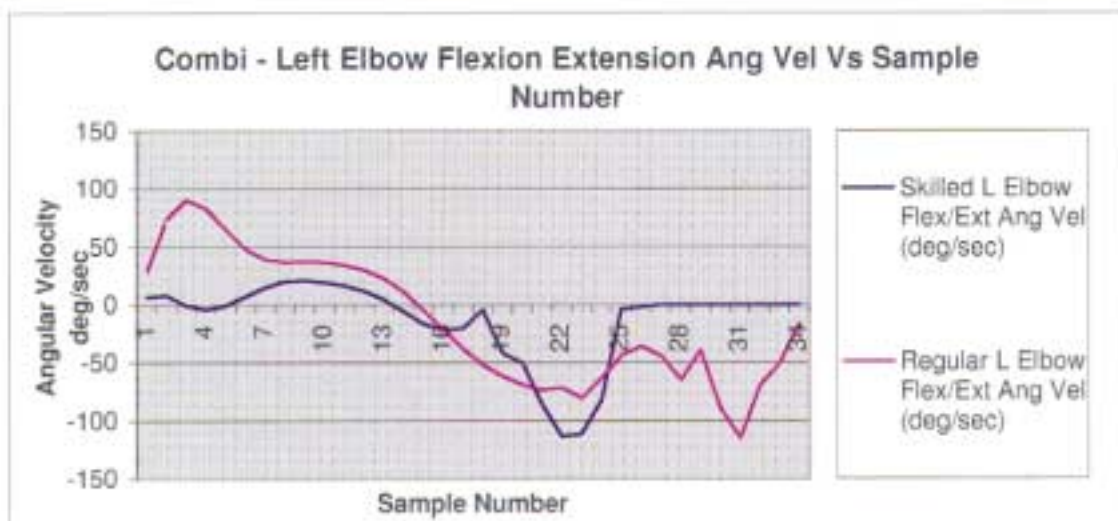
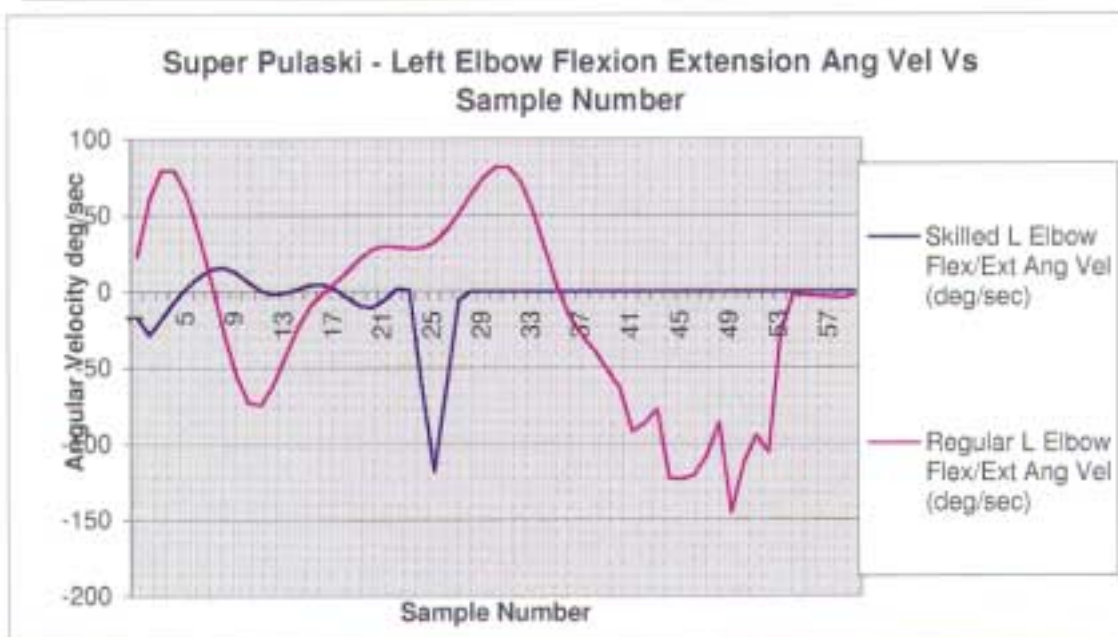
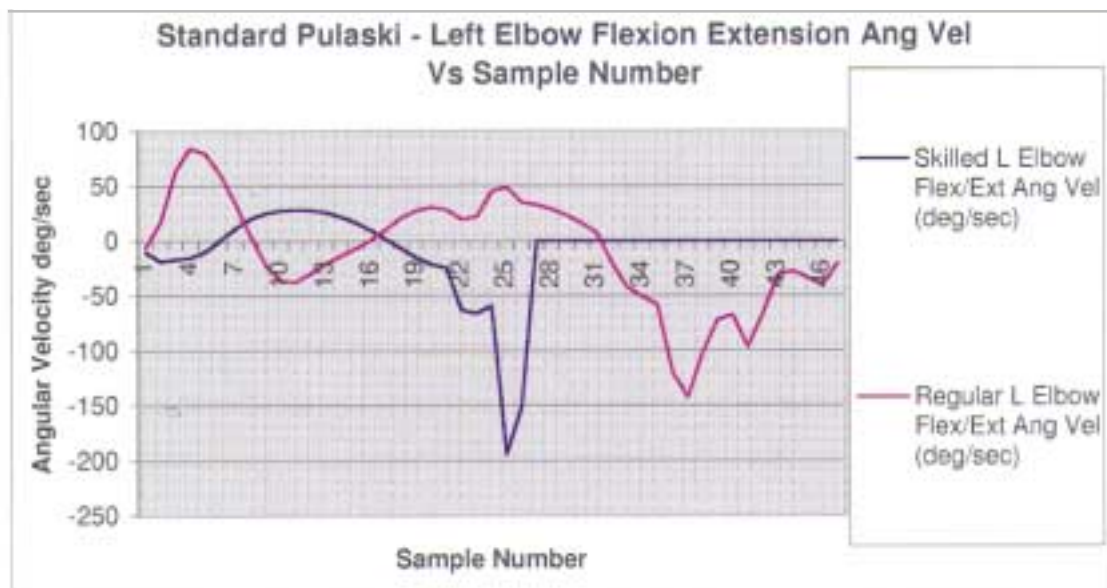


Figure 21—Left wrist flexion/extension angular velocity.

The Super Pulaski has a 6.8-inch hoe blade. The regular worker with 40 strikes per minute can strike/grub 272 inches per minute. The skilled worker with 75 strikes per minute can strike/grub 510 inches per minute.

The same body postures at maximum tool height and tool strike, and the same key angles were examined for the Super Pulaski that were evaluated for the standard Pulaski. Variability of these body postures was similar, 3 to 6 degrees between groups. See tables F2 and F3.

In general, the full ranges of motions were larger for regular workers with the use of a Super Pulaski, as compared to skilled workers. See table F4. As with the standard Pulaski, this is easily observed as regular workers used arm and shoulder muscles for grubbing; and skilled workers used leg and trunk muscles mainly for grubbing.

Based on the examination of body postures at maximum tool height and tool strike, the shoulder position and wrist angle are important in determining the skill level of a worker using a Super Pulaski.

Key points determined in this kinematic analysis of the use of the Super Pulaski are:

- The biomechanic values measured in the joint angle profiles with the Super Pulaski, reveal patterns similar to the Standard Pulaski, except that differences between regular and skilled workers are more pronounced and distributed among a greater number of the joints.
- Regular workers perform the first half of the motion similar to that of a skilled worker and draw the second half of the motion out and perform it much more slowly, even longer than with the standard Pulaski.

- Regular workers perform one motion cycle for every two completed by a skilled worker.
- Regular workers impact the tool head with twice the force used by skilled workers.
- Regular workers elevate the tool head 100 percent higher than a skilled worker.
- Regular workers expend the same amount of energy in one cycle that is expended by a skilled worker in two cycles, simply by lifting the tool head higher.
- The full range of motions was larger for regular workers as compared to skilled workers.
- Shoulder position and wrist angle are important in determining the skill level of a worker using a Super Pulaski.
- As with the standard Pulaski, regular workers used arm and shoulder muscles for grubbing; skilled workers used leg and trunk muscles for grubbing. Consequently regular workers are expected to fatigue much more quickly due to the size difference of these muscles.
- The Super Pulaski has a 6.8-inch hoe blade. The regular worker with 40 strikes per minute can strike/grub 272 inches per minute. The skilled worker with 75 strikes per minute can strike/grub 510 inches per minute.
- Previous fire tool studies have shown that the increased energy costs far out weight any production gain.

Combi Tool

The joint angle profiles of regular and skilled workers are the most similar for use of the Combi tool, when compared with the standard and Super Pulaskis.

This indicates that the Combi tool would be the easiest tool to train regular firefighters to become skilled firefighters. See figures 11 and 15.

Left and right shoulder angle profiles are similar for regular and skilled workers with the use of the Combi tool, except that the flexion/extension range of motion was larger for regular workers. See figures 16, 17, and 22 for the left shoulder and figures 11, 23, and 24 for the right shoulder. The joint angle profiles for the right elbow and wrist, and left elbow and wrist are similar, except for the right wrist flexion/extension angle. See figures 15 and 25 for the elbows and figures 18 and 19 for the wrists. The right wrist flexion/extension profile for a regular worker is almost a mirror image of the profile for a skilled worker. Peak angular velocities are generally higher in regular workers, with the largest differences seen in the left wrist and elbow. See table F1 and figures 20 and 21. The hand separation for regular workers on the average was 16 inches, and 23 inches for skilled workers. See figure 10.

Although there are only minor differences in the joint angle profiles between regular and skilled workers, there are significant differences in motion cycle time, tool impact force, and tool lift height. See figures 6, 7, and 8. Regular workers had an average cycle duration of 0.9 seconds, 67 tool strikes per minute, tool impact force of 3.0 gs, and lift height of 21 inches. Skilled workers had an average cycle duration of 0.7 seconds, 86 strikes per minute, tool impact force of 1.8 gs, and lift height of 12 inches. Tool impact force and lift height for regular workers are approximately 70 percent greater than skilled workers. In addition, regular workers require an average of 40 percent more time to complete a grubbing cycle, as compared to skilled workers. The lift height used by skilled workers is approximately 12 inches.

This does not seem intuitive until the additional length of the Combi handle is considered. This is the lowest energy cost of the tools tested.

Skilled workers can complete 86 tool strikes for every 67 by a regular worker, or an increase of

28 percent in productivity. The same standard hand crew production rates for medium brush for a line width of 6 feet as described with the standard Pulaski were used. A 28 percent increase in productivity can increase line by 55 feet per hour if the whole crew was trained to the skilled level. That is comparable to having 2 people added to a 15-person crew. Again, this is based on the assumption that half the crew is already skilled. It is important to note that the tool strike/grub rate for the Combi tool for regular workers is high compared to values reported for the standard Pulaski and Super Pulaski. Consequently, the difference between regular and skilled worker with the Combi tool is best described by taking into account the blade width versus strike rate, as follows.

The Combi tool has a 4-inch serrated blade. The regular worker with 67 strikes per minute can strike/grub 268 inches per minute. The skilled worker with 86 strikes per minute can strike/grub 344 inches per minute. The Combi tool is the most efficient tool based on the low energy cost, high productivity, and safety aspects, especially for the regular firefighter.

Body posture at maximum lift height and tool strike with the use of the Combi tool did not vary to the same level of differences between regular and skilled workers, as observed with the standard and Super Pulaskis. See tables F2 and F3. This indicates the Combi tool is a better tool for regular firefighters as skills are developed.

Body position at the maximum tool lift height had slightly more variability, with 3 to 7 degrees for regular workers and 2 to 4 degrees for skilled workers. A 7-degree variation of regular right shoulder flexion/extension angle is relatively large in comparison to the other levels of variability. Body position at tool strike indicated a similar variability of 3 to 5 degrees for regular and skilled workers.

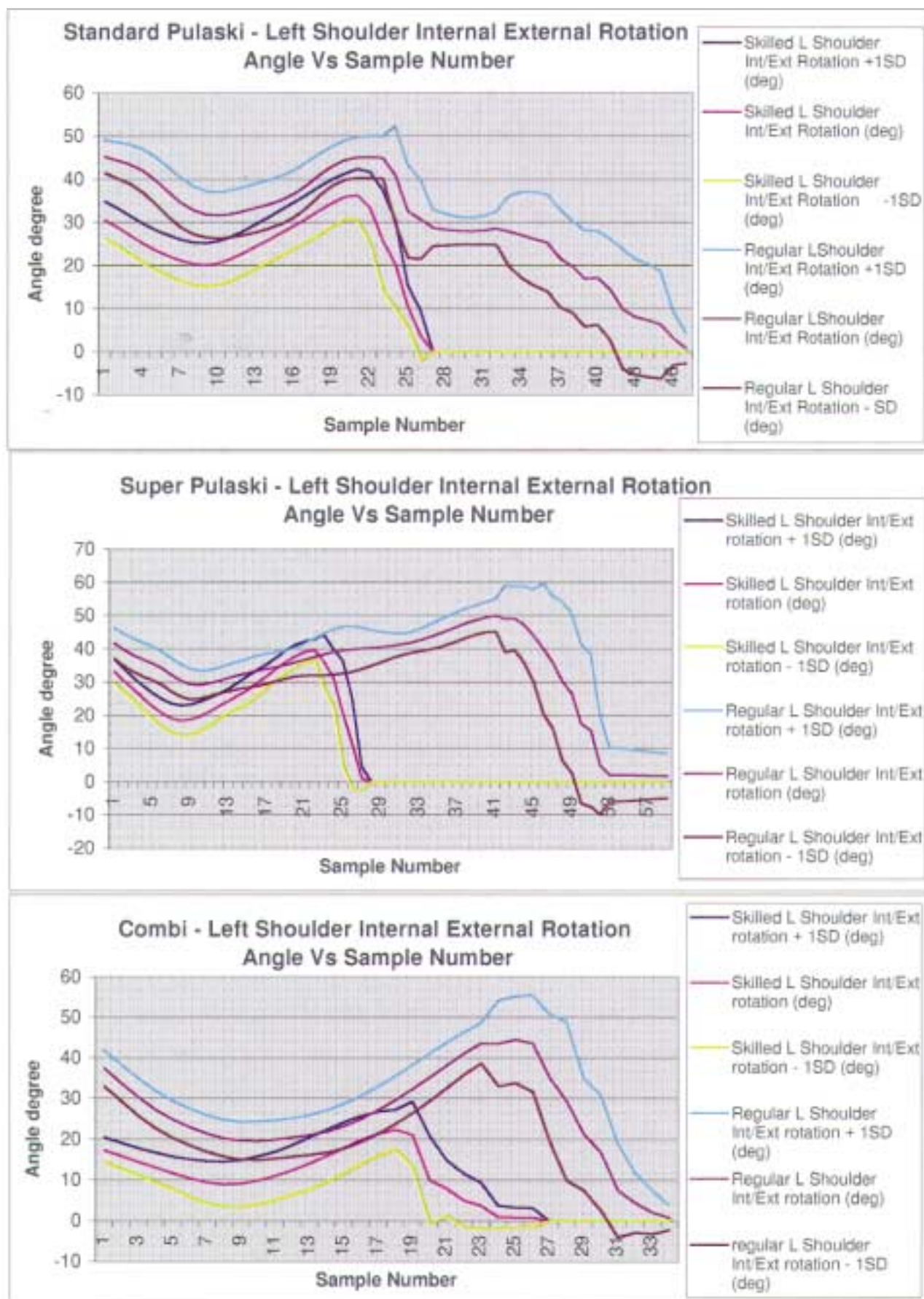


Figure 22—Left shoulder adduction/abduction angle.

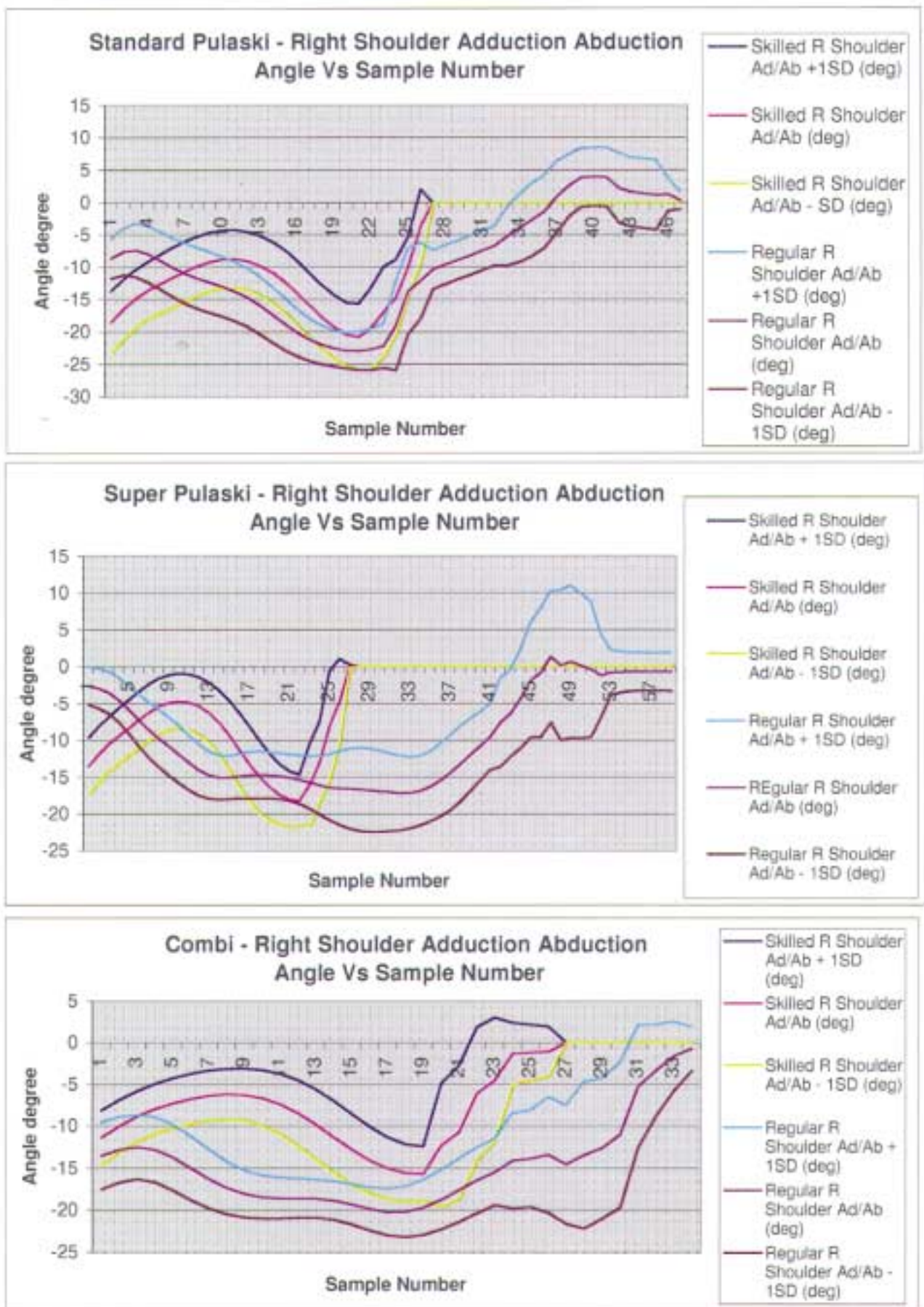


Figure 23—Right shoulder adduction/abduction angle.

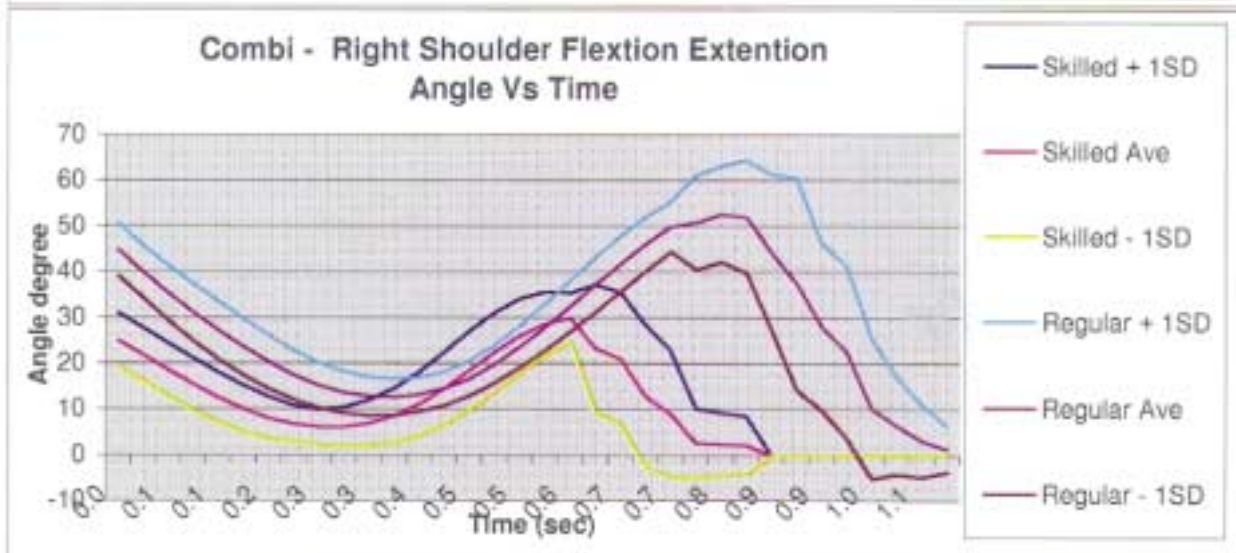
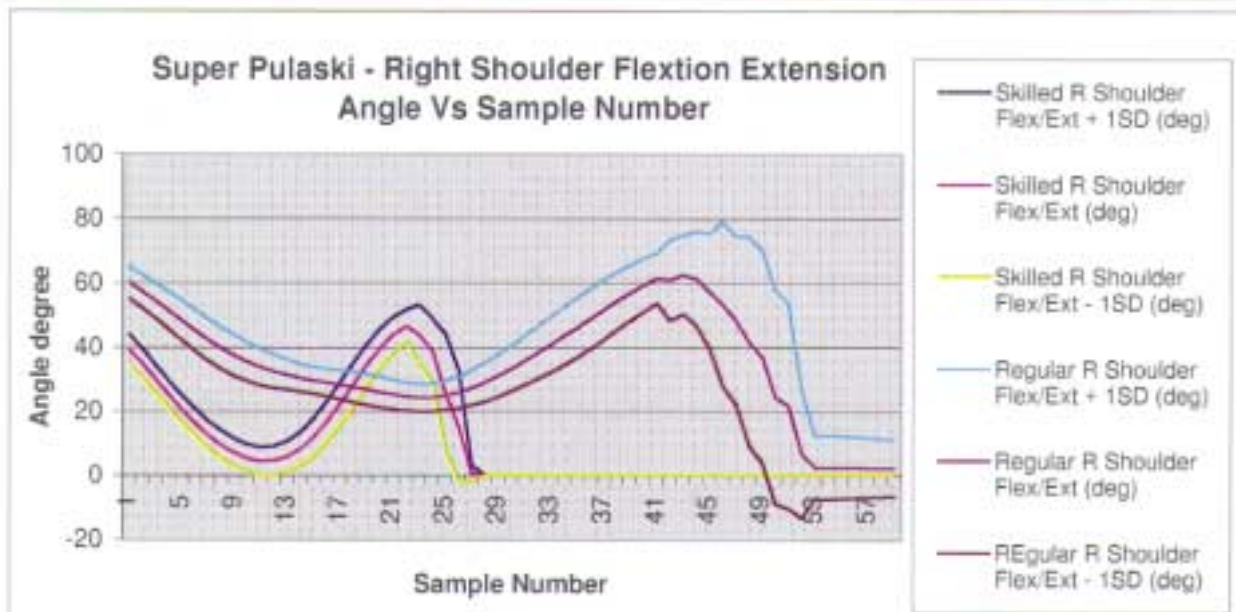


Figure 24—Right shoulder flexion/extension angle.

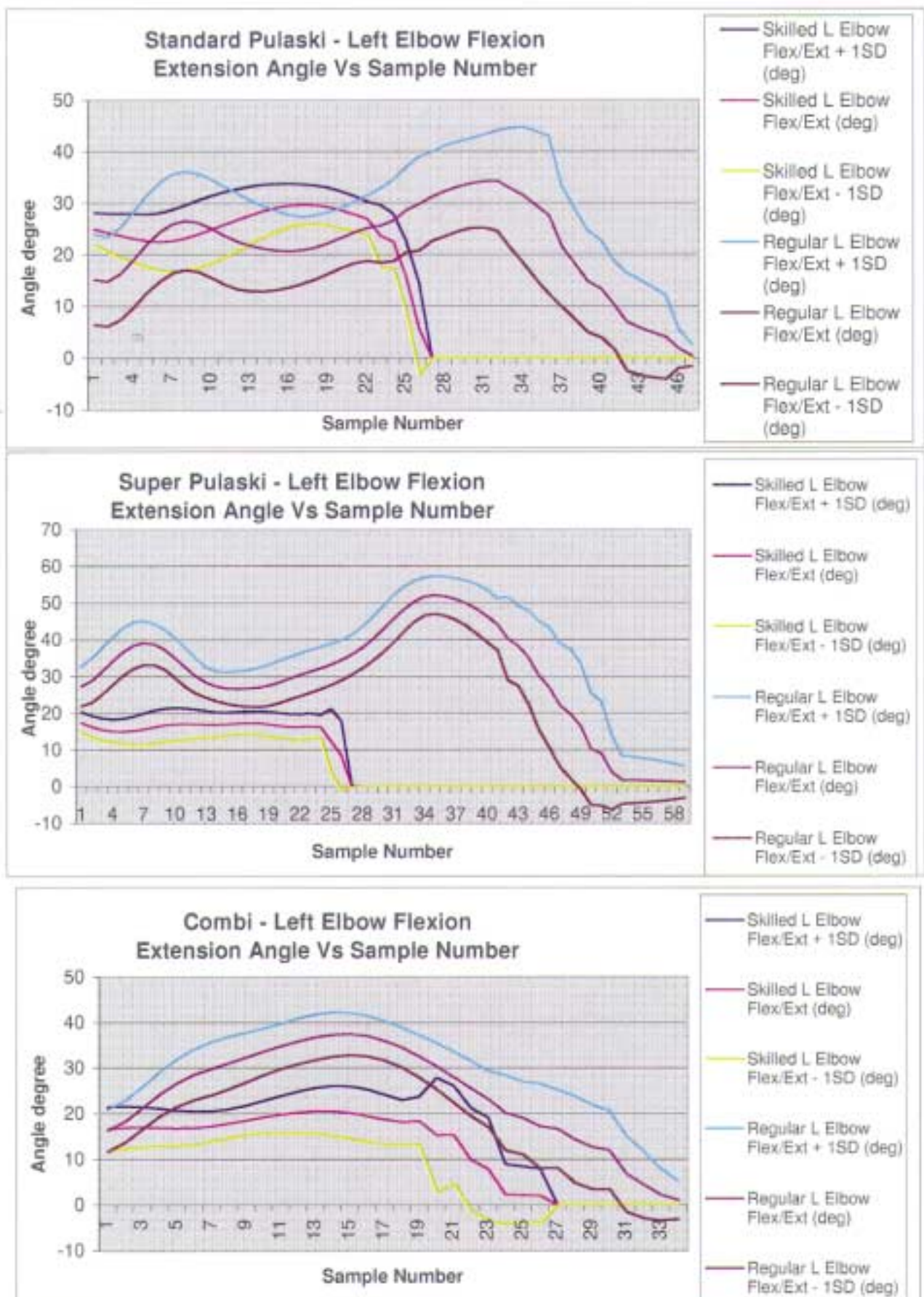


Figure 25—Left elbow flexion/extension angle.

Regular workers continued to be observed using arm and shoulder muscles for grubbing with the Combi tool, but were also observed using some leg and trunk muscles. The skilled workers continued using leg and trunk muscles for grubbing with the Combi tool. Consequently, regular workers are expected to fatigue quicker with the standard and Super Pulaski when compared to the Combi tool.

This further substantiates that the Combi tool is the most efficient tool for regular firefighters as skills are developed.

Based on the examination of body posture at maximum tool height and tool strike, the shoulder position is important in determining the skill level of a worker using a Combi tool.

Key points determined in this analysis of the use of the Combi tool are:

- Joint angle profiles of regular and skilled workers are the most similar for use of the Combi tool, as compared to the standard and Super Pulaskis.
- Left and right shoulder angle profiles are similar for regular and skilled workers, except that the flexion/extension range of motion was larger for regular workers
- The right wrist flexion/extension profile for a regular worker is almost a mirror image of the profile for a skilled worker.
- Peak angular velocities are generally higher in regular workers, with the largest differences seen in the left wrist and elbow.
- Hand separation profiles are very similar between regular and skilled workers.
- Regular workers perform the first half of hand separation and right shoulder motion similar to that of a skilled worker, drawing the second half of the motion out and performing it more slowly.
- Regular workers perform two motion cycles for every three completed by a skilled worker.

- Regular workers impact the tool head with 70 percent more force than skilled workers.
- Regular workers elevate the tool head 70 percent higher than a skilled worker.
- Regular workers expend the same amount of energy in three cycles that is expended by a skilled worker in two cycles, simply by lifting the tool head higher.
- Body posture at maximum lift height and tool strike did not vary to the same level of differences between regular and skilled workers, with the standard and Super Pulaskis.
- Shoulder position is important in determining the skill level of a worker using a Combi tool.
- The Combi tool is a better tool for regular firefighters as skills are developed.
- Regular workers are expected to fatigue quicker with the standard and Super Pulaski as compared to the Combi tool.
- The Combi tool has a 4-inch blade. The regular worker with 67 strikes per minute can strike/grub 268 inches per minute. The skilled worker with 86 strikes per minute can strike/grub 344 inches per minute.
- The Combi tool is the most efficient tool based on the low energy cost, high productivity, and safety aspects, especially for the regular firefighter.

DETAILED DATA ANALYSIS BY BIOMECHANICAL PARAMETER

Overall the skilled workers generated smoother, more consistent motions for the entire group over the entire cycle of motion. Conversely, regular workers had more variation in the motion for the entire group over the entire cycle. Plus or minus a standard deviation is a measure of the variation from the average motion for the group. See

figures 10 through 25, and appendixes E and F. Typically, the standard deviation is wider for regular than for skilled workers across all biomechanical parameters measured. Generally, biomechanical analyses reveal that a group of skilled workers performs a task more consistently, i.e., the standard deviation is significantly smaller than a group of regular workers performing the same motion.

Tool Acceleration/Force At Impact

With respect to tool acceleration at impact, a measure that is equivalent to force, both groups maintain a consistent impact force per pound of tool with the regular worker impact force nearly 145 percent that of the skilled worker. See figure 10. This is partially due to the increased lift height and the increased angular velocity resulting from the extended reach of regular workers. See figures 3 and 14. This is going to cause increased work on the back for two reasons. First, back exertion will be required to support the motion. Secondly, the tool will be buried further into the ground causing more strain on the back to free the tool blade to complete the motion cycle. See figure 26.



Figure 26—Increased work from increased lift and extended reach by regular workers.

Key points determined in this kinematics analysis of the tool acceleration/force at impact are:

- The average impact force for all tools, delivered by the regular worker is nearly 145 percent that of the skilled worker.
- This is partially due to the increased lift height and the extended reach of regular workers, increasing the potential for back strain.

Tool Lift Height

Tool lift height is another factor contributing significantly to an increased regular cycle time. Interestingly, the heavier the tool, the higher the regular worker lifted the tool. See table 1 and figure 14. On the other hand, the skilled worker decreases the height for an increased tool weight.

Compare the lift height graphs for the three tools. This gets back to the use of momentum and gravity. Skilled workers appear to use the same amount of power regardless of tool weight. This can be considered pacing, in order to maintain a sustainable work rate. Skilled workers may be working at maximum energy output, so they vary technique to maintain constant power output. Skilled workers vary lift height according to tool weight, less lift for more given weight. This is due to gravity contributing more significantly to the motion, in terms of momentum, due to an increased weight. **Consequently, it follows that regular workers should start learning with a lighter tool until control of power and technique are learned, then progress to heavier tools.**

Key points determined in this kinematic analysis of tool lift height are:

- Regular workers lift the tool 50 percent, 100 percent, and 70 percent higher than skilled workers for the standard Pulaski, Super Pulaski, and Combi tool respectively.
- The higher the tool lift, typically the longer the cycle time.

-
- The heavier the tool, the higher the regular worker lifted the tool.
 - The heavier the tool, the lower the skilled worker lifted the tool.
 - Skilled workers appear to use the same amount of power regardless of tool weight.
 - Regular workers should start learning with a lighter tool until control of power and technique are learned, then progress to heavier tools.

Work Cycle Time

Skilled workers keep the work cycle time nearly the same, regardless of handle length or tool weight. Skilled workers keep the energy level required to perform a motion uniform, resulting in a sustainable work rate. In other words, skilled workers know how to pace themselves based on the tool, for all tools. Regular workers do not appear to pace themselves. This may be the reason for reports that they fatigue more quickly and severely with increased tool weight. This also causes the regular worker to require a longer recovery time. When the regular worker lifts a heavier tool higher, the tool comes down with a greater force, due to the increased vertical distance and increased mass. The regular worker uses greater care in hand position, contributing to increased energy requirements and cycle time. Because of this, regular workers bury the tool blade into the soil further than skilled workers, making it necessary to jerk the tool from the soil, further compounding the energy needs for the task. The consistency of skilled cycle time and increased regular cycle time is illustrated in figure 10.

Tool Head Path—Position and displacement graph of the path of travel of the tool head. See figures 27 and 28.

Hand Separation

Hand separation performance graphs for the standard Pulaski indicate that regular and skilled workers begin the motion with their hands in the same position. However, skilled workers pull their

hands together much faster than regular workers as they bring the tool in a down swing.

It appears that skilled workers are using one power generating arm/hand and one guiding hand. The regular workers appear to separate power generation from tool guidance. By having tool guidance in a second phase, the regular worker does not take advantage of the tool's natural momentum from the pull of gravity. As a result, regular workers are “fighting” the natural fall of the tool, increasing the workload. Regular workers start in the same position, but use both hands to control the tool path throughout the complete swing, causing the cycle time to be prolonged.

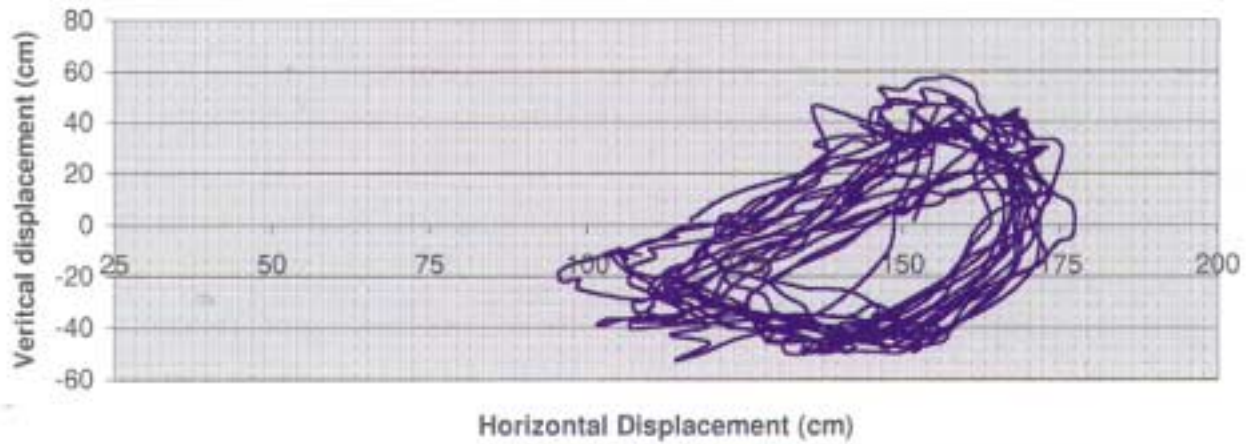
A comparison of hand separation graphs for the standard Pulaski, Super Pulaski, and Combi tools indicates that this is a weight dependant issue. See table 1 and figure 10. The lighter the tool and the longer the handle, the further apart skilled workers positioned their hands. The opposite is true of regular workers, especially in the last half of the motion. Skilled workers snap their hands together. Regular workers gradually pull their hands together slowly, in order to maintain greater control over the tool head. An examination of the skilled standard deviation during the first half of the motion shows that heavier tools require greater consistency of motion. This is one of the factors contributing to increased cycle time.

Wrist Rotation Joint Angle Profile

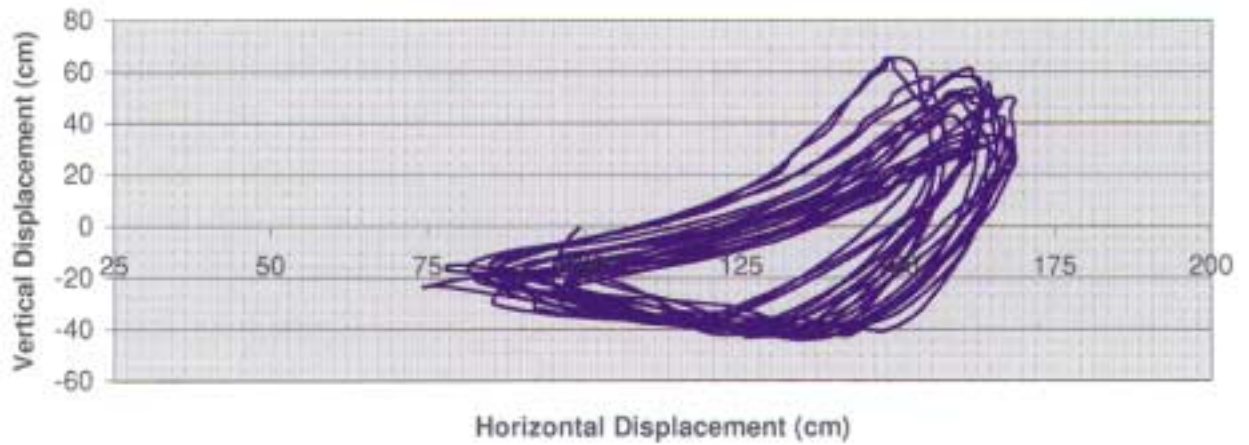
Recall that the area under the joint angle curves is a measure of the energy exerted during the motion. For example, the area under all joint profile curves is much greater for regular workers than for skilled workers across all biomechanical parameters measured. See figures 10 through 25, and appendixes E and F.

This increased energy input and lack of tool control by regular workers, specifically with the

Standard Pulaski - Tool Head Path - Regular 1



Standard Pulaski - Tool Head Path - Regular 2



Standard Pulaski - Tool Head Path - Regular 4

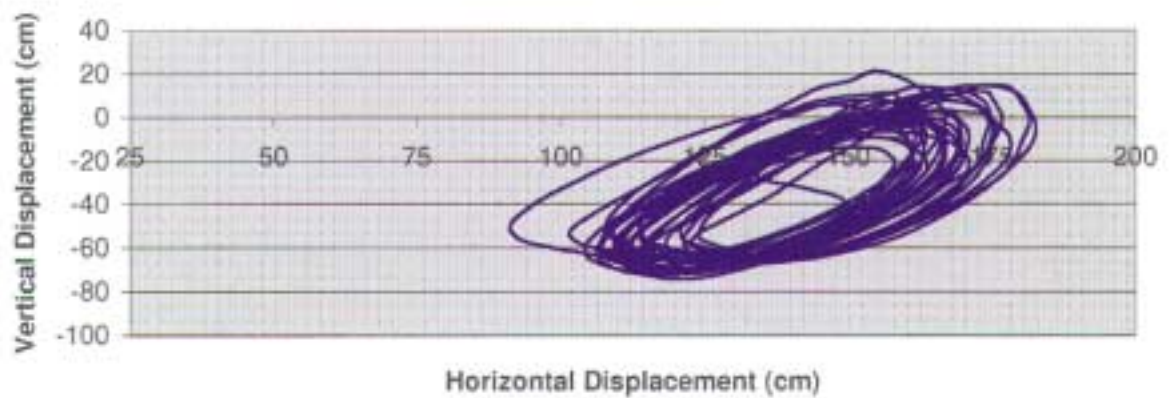


Figure 27—Standard Pulaski tool head path, regular workers.

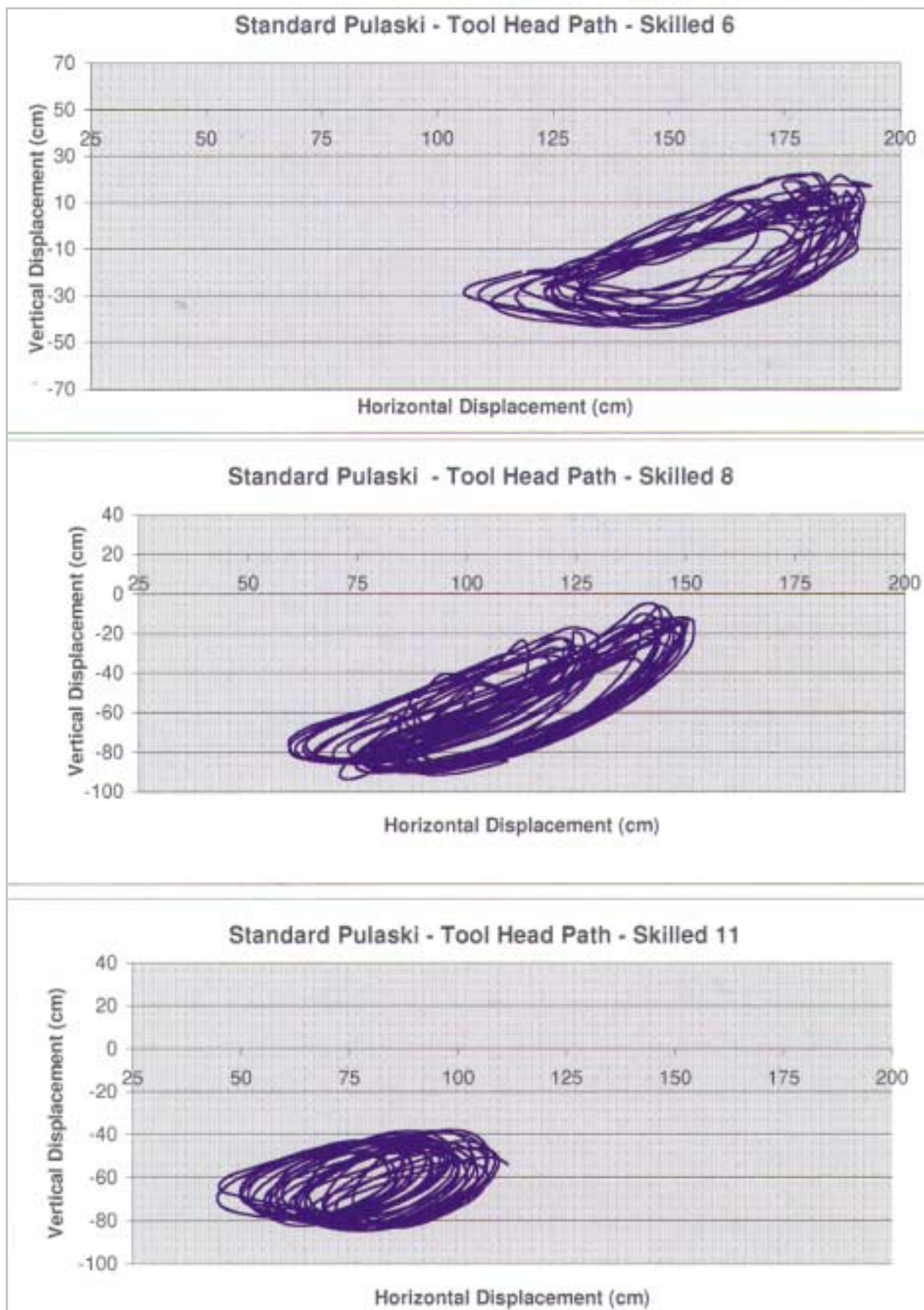


Figure 28—Standard Pulaski tool head path, skilled workers.

Super Pulaski, causes a safety concern. This is illustrated by the bandwidths and irregularity of performance graphs for regular workers. The Super Pulaski is typically a non-scientific field modification of the standard Pulaski, with an increase in mass on the hoe blade, with no apparent design consideration given for the resultant change in the dynamics/tool balance caused by this increase in mass. When one blade of a dual tool head is changed, the entire tool head needs to be redesigned/re-balanced to keep the center of gravity and center of percussion along the tool handle centerline (3). For the Super Pulaski, the increase in mass on the hoe blade has moved the center of gravity and center of percussion further away from the handle centerline as compared to the standard Pulaski. Consequently, the angular acceleration increases, causing an increased impact rotation. This is sensed by the firefighter as increased handle twist on impact, stinging hands and increased onset of fatigue. Furthermore, changing the tool head mass on the hoe side without balancing the entire tool head may affect the proper use of the chopping blade by creating chopping limitations, again, compromising safety.

Regular and skilled workers react to this twisting force differently. These differences are evident in the right wrist internal-external rotation joint angle profiles. The graph for the standard Pulaski, a nearly balanced tool head, shows that both skilled and regular workers utilize wrist internal-external rotation similarly. However, the Super Pulaski curve is quite different so far as the regular worker is concerned. The skilled worker duplicates the standard Pulaski motion with a slight increase in rotation to compensate for the imbalance, while the regular worker allows the tool to twist by providing no resistance via wrist rotation. See figure 29.

The increase in tool head weight of the Super Pulaski does increase wrist rotation throughout all cycles for skilled workers. However, regular workers allow the Super Pulaski to freely rotate through the whole cycle. This is a critical safety

concern. The regular worker has a freely rotating, sharp edged Super Pulaski, impelled by a considerable amount of momentum directed with the tool blade angled toward the non-dominant foot. See figure 30. A time lost accident study to evaluate this safety concern is prudent. Firefighters have noted an increase in tool rotation on impact and this may be a strong contributing factor. Further study is warranted regarding lost time accident studies and worker compensation for carpal tunnel and low back injuries associated with the use of fire hand tools. Furthermore, a study to determine the optimum hoe blade width for a balanced Pulaski using rigorous scientific methodology would be prudent and cost effective from a production and safety perspective.

Shoulder Flexion/extension Angle and Arm Reach

Examination of the right shoulder flexion/extension angle shows a regular worker increases arm reach. See figures 10 and 24. The significance of increased reach is an increased loading of the lower back, which translates to earlier fatigue of the lower back, increasing the potential for back injury. Regular workers start the grub motion cycle with the right shoulder flexion/extension angle at 22-degrees open for the standard and Super Pulaski and 12-degrees open for the Combi tool. By contrast, skilled workers start uniformly at around 6-degrees open for all tools. The regular worker increases the right shoulder flexion/extension angle by 18 degrees and the skilled worker by 34 degrees with the standard Pulaski. Regular and skilled workers both increase the angle by 40 degrees with the Super Pulaski. Interestingly, regular workers increase the angle by 40 degrees with the Combi tool, as compared to skilled workers increasing by 24 degrees. This may be due to the regular worker using only arm and shoulder muscles with the standard and Super Pulaski and adding the use of leg and trunk muscles with the use of the Combi tool only. Skilled workers predominantly use only leg and trunk muscles for all tools.

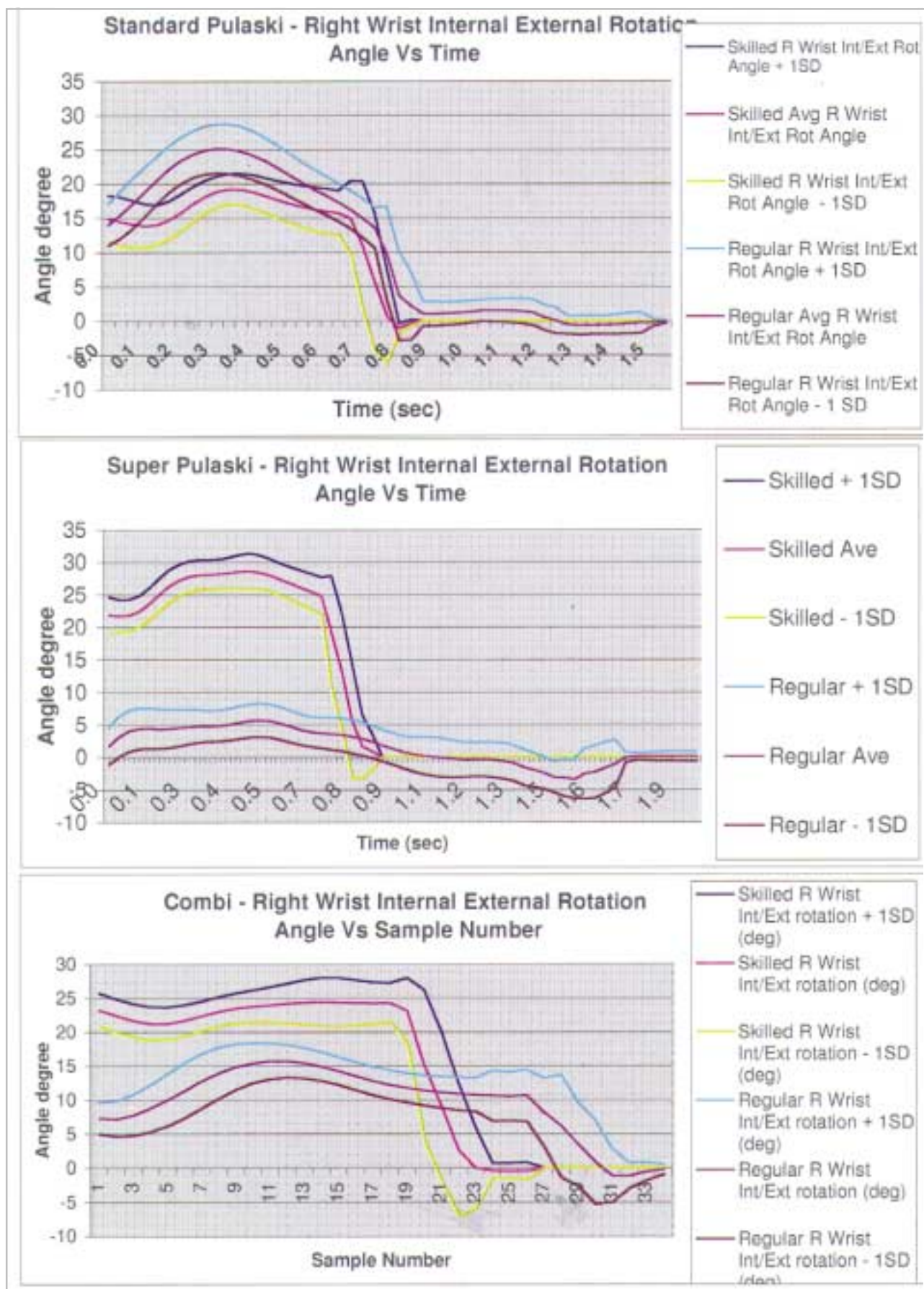


Figure 29—Standard Pulaski, Super Pulaski, and Combi Tool—Right wrist internal external rotation.

REGULAR WORKER

- Regular workers typically have the non-dominant foot slightly forward and intersecting the tool path.
- The knees are flexed and the back may or may not be straight.
- The regular worker is bent at the waist and back not parallel to the ground; more upright.
- There is an up and down, bobbing motion of the back. Arm and shoulder muscles are used for grubbing.
- The tool blade is angled towards the non-dominant foot in the tool swing path. However, the tool swing stops short of the foot.
- The increased arm reach of the regular worker may also be a method of compensating for the difference in body posture relative to the fire line as compared to the skilled worker.

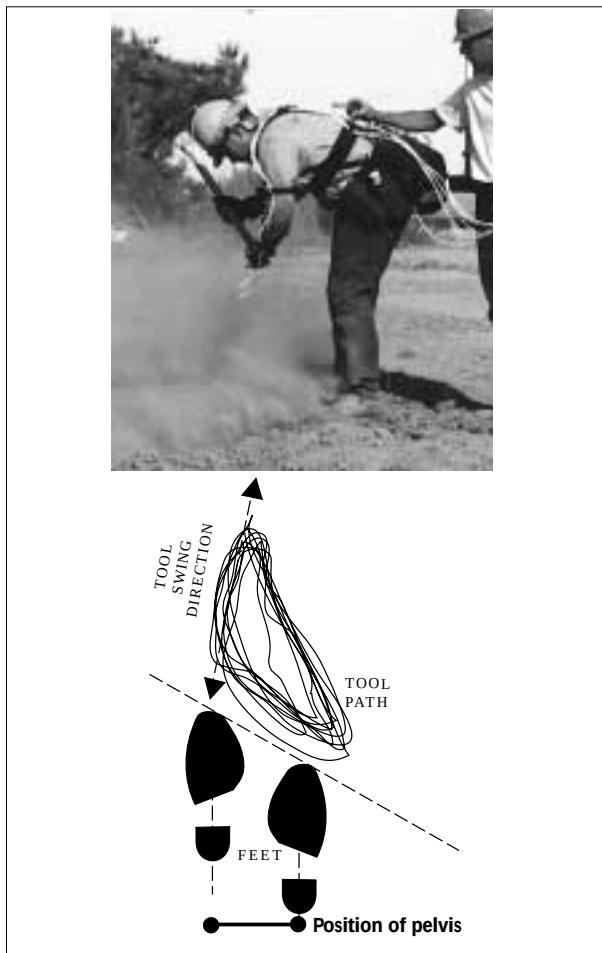


Figure 30—Regular worker body posture and tool swing path.

SKILLED WORKER

- Skilled workers tend to have the dominant foot slightly forward and essentially parallel to the tool path; non-dominant foot 60 degrees off the dominant foot.
- Knees flexed; back straight; bent at the waist at an angle almost parallel to the ground;
- The tool blade angled away from the body, with feet positioned out of the way of the swing of the tool blade.
- During the tool swing, back position is kept almost steady.
- Uses leg and trunk muscles for grubbing. See figure 31.

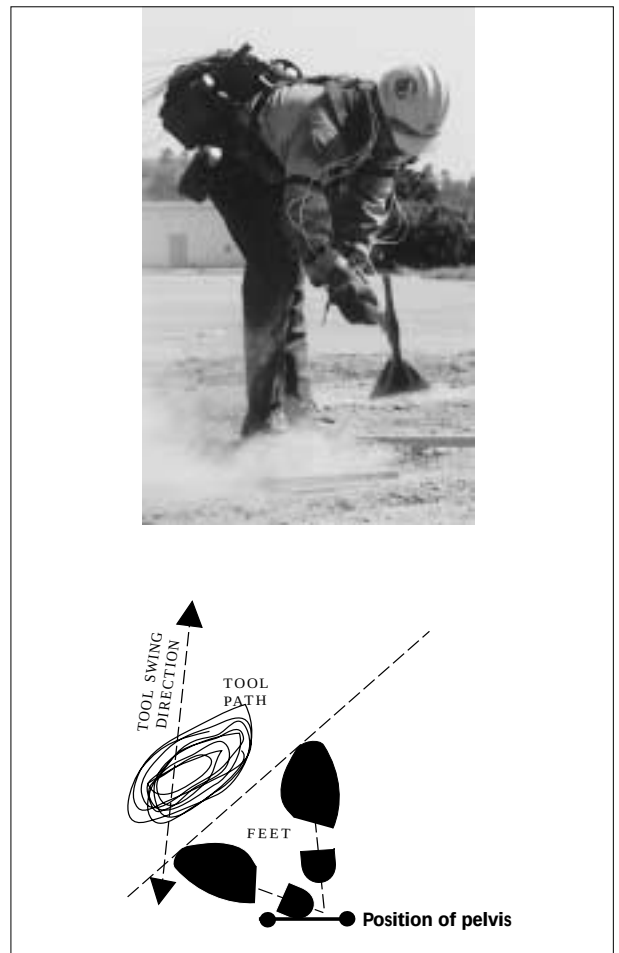


Figure 31—Skilled worker body posture and tool swing path.

This positioning combined with the difference in hand separation contributes to the drastic difference observed in left shoulder flexion/extension in the Super Pulaski. See figure 17. The regular worker has the front, non-dominant hand further down the tool handle as the blade drops. Again increasing the loading on the lower back because the regular worker is stretched out and more stooped over. See figures 22, 23, and 24.

Critical Biomechanical Parameters

Based on the results of the comparative analysis, a determination was made that there are five controlling parameters that describe the optimum body position and tool swing technique, using primarily leg and trunk muscles for the skilled use of fire hand tools. Furthermore, all other parameters discussed will fall in line including the primary use of leg and trunk muscles once these principle factors have been implemented:

- Positioning of feet and body in the skilled workers posture with a tool swing path as described in figure 31.
- Tool lift height not to exceed 20 inches for the standard Pulaski, 23 inches for Super Pulaski, and 12 inches for the Combi tool.
- A work cycle time of 0.8 second or stroke rate of 75 strikes per minute for the standard and Super Pulaskis. A work cycle time of 0.7 second or stroke rate of 86 strikes per minute for the Combi tool.
- A hand separation of 16 inches for the standard and Super Pulaskis, and 23 inches for the Combi tool.
- Starting grub cycle with a right shoulder angle of 6 degrees when leading with the right hand and vice versa with left hand.

Proposed Training Program

Skill development is achieved through instruction and practice. A practical training program ensures greater success of implementation. The following training has been developed to implement the five principle factors of skilled grubbing and the primary use of leg and trunk muscles: tool lift height, work cycle time, hand separation, right shoulder angle and position of feet. Train to these principles one step at a time. It is important to fully master each principle before moving to the next principle. Start with the Combi tool and progress to the standard Pulaski when the worker is skilled at the use of the Combi tool.

This training program requires further refinement, including results verification, before implementation.

Position of Feet Relative to Fireline—Positioning of feet in the skilled worker posture as described in figure 31.

Tool Lift Height—Obtain three wooden stakes and brightly colored wooden dowels, rulers or sticks. Mark off 3 inches from the bottom tip of the first stake with a permanent marker. Write “ground” just below the mark. Pound the stake into the ground until the word “ground” can no longer be seen. Measure 20 inches above the ground mark and mark this level “Pulaski”. Secure a colored dowel at this point, perpendicular to the stake. See figure 32. Repeat the procedure with the other 2 stakes and colored dowels, except use 23 inches for the Super Pulaski and 12 inches for the Combi tool. An alternative method would be to use flagging, tied to the tool head at the handle, measured to the proper length, with a wad of flagging added to the end to add a little weight. String or cord could also be used with the same method. These materials are readily available at fire camp, and could be used to alert regular firefighters to the proper tool lift height.



Figure 32—Tool lift height indicator with a stake and colored dowels.

Stroke Rate - Work Cycle Time—Use a tape recording of a metronome set at 75 beats per minute or buy a metronome at a local music instrument shop. Cost for a battery powered metronome with a loud beep and a speed range of around 75 beats per minute is \$12 to \$22. The work cycle time for a complete stroke is 0.8 second, which equals 75 beats per minute for the standard and Super Pulaskis. The work cycle time for the Combi tool is 0.7 second or 86 beats per minute. Workers can speed up or slow down in pace with the metronome. See figure 33.



Figure 33—Pace tool strikes with a metronome.

Hand Separation—Obtain a 36-inch length of 1-inch elastic band. This can be easily obtained from the notions section of a general-purpose store for a cost of around \$1.00. Measure off 2 inches and mark; continue with 16 more inches and mark with a “Pul”; continue with 7 more inches and mark “Com”; measure 2 more inches and cut. Loop and tie the ends of the elastic to the wrist straps of each glove at the appropriate mark for the tools in use. The hand separation for the standard Pulaski and Super Pulaski is 16 inches, and 23 inches for the Combi tool. See figure 34.



Figure 34—Hand separation maintained within set parameters by elastic cord.

Right Shoulder Angle—Buy a 10-ounce plastic sack of rice. Open the plastic sack at the end. Pour out half of the rice and fold over the end of the sack onto itself. The sack should be about 3 x 4 inches and loosely filled. Wrap securely with duct tape, keeping the sack still loose in general shape. Attach a short cord to the rice sack. Use duct tape to secure the bag into position approximately 3 inches below the armpit of your shirt on your non-dominant side/arm, usually the left arm of most people. Another method is to secure the rice bag in position with a short cord around the rice bag and the other end attached to your fire shirt. Position the rice bag into place 3 inches below the armpit and against the upper torso by applying pressure with the upper arm. See figure 35. Attempt to maintain the bag against the torso, especially in the up-stroke phase. This will maintain a narrow right shoulder angle and short arm reach.



Figure 35—Bag in position to maintain a narrow right shoulder angle and arm reach.

Participant Ranking of Tools

After using all three tools, the workers were asked to rank each tool in comparison with the other tools for eight different features. Test worker ratings were averaged for the group, on a scale from negative 5 to positive 5. Participant rankings of the three test tools are shown in table 2.

Table 2—Participant Ranking of the Standard Pulaski, Super Pulaski, and Combi Tools

	Regular			Skilled		
	Standard Pulaski	Super Pulaski	Combi	Standard Pulaski	Super Pulaski	Combi
Quality of Line	0	2	-5	3	5	4
Effectiveness	1	1	-1	3	5	1
Versatility	0	0	2	4	2	3
Less Fatigue—Hand and Arm	-1	-3	3	-3	-4	1
Less Fatigue—Lower Back	2	1	3	-3	-4	1
Safety—Control	1	-1	4	4	2	1
Less Shock—Handle absorption	2	1	2	2	1	4
Better Grip	2	0	4	2	1	4
Key for Ranking						
Most Negative = -5			No Difference = 0		Most Positive = +5	

The standard Pulaski was ranked high by skilled workers for versatility and safety; low by both groups for quality of line and effectiveness; and fair on grip and shock absorption of handle.

The Super Pulaski was ranked high for both groups for quality of line and effectiveness; ranked high for causing fatigue in arms, and lower back; and ranked low in safety/control and versatility.

The Combi tool was ranked high by both groups for grip, shock absorption of handle, reduced back, and arm fatigue. The Combi tool was ranked high by regular workers for versatility and safety/

control, but ranked low for the same factors by skilled workers.

The Combi tool was ranked low by both groups for quality of line and effectiveness. However, test results in this study, as described in a previous section, show that use of the Combi tool provides a higher productivity, lower energy cost, and higher safety aspects than the standard or Super Pulaski. This is indicative of a strong tool bias. This is an indicator that the benefits of the use of the Combi tool have not been fully realized.

Experience, Strength, and Fitness Scores

Experience, strength, and fitness scores are shown in table 3.

Table 3—Experience, Strength and Fitness Scores

	Regular	Skilled
Number of fires fought, average	168	127
Number hours digging line, average	1,816	2,200
Height average	5 ft 8 in	5 ft 9 in
Height range	5 ft 8 in - 5 ft 9 in	5 ft 4 in – 6 ft 2 in
Weight pounds	176	164
Weight range pounds	163 to 192	135 to 202
Age, years	33	30
Gender	F, F, M	M, F, M
Percent body fat	33	22
Number chin-ups	5	12
Chin up range of values	0 to 15	6 to 20
Right hand grip force, pounds	121	116
Left hand grip force, pounds	112	113
1-1/2 mile run	13 min 38 sec	9 min 46 sec

The best indicator for work capacity is the pack test. Pack test results were not available for all test participants and are not included.

The time required for the 1-1/2 mile run was 40 percent higher and percent body fat was 50 percent higher in regular workers as compared to skilled workers. These are significant differences in levels of physical fitness critical to firefighter performance with the potential for

accidents or injury. An appropriate minimum performance standard, based on physical requirements for skilled firefighters, is crucial to safety. In addition, it is important to have a reserve available for use in emergencies. Specific steps for wildland firefighters to achieve and maintain fitness and work capacity are well described in the National Wildfire Coordinating Group publication “Fitness and Work Capacity” (20).

Participant Comments

In the survey, regular and skilled workers were asked to comment on the test tools. Their comments are summarized in table 4.

Table 4—Summary of Comments From regular and Skilled Workers

• <i>Standard Pulaski - I like the balanced weight as compared to the Super Pulaski. I dislike the back fatigue. Weight of tool on downswing is the key.</i>
• <i>Combi tool is easy to use, feels light. Handle diameter is too big, so can't get a good grip.</i>
• <i>I like the big grub end of the Super Pulaski. I think it's more efficient, but I don't like the odd balance on the head.</i>
• <i>The Super Pulaski does not require as much effort to pound, just let it drop and pull it.</i>
• <i>Combi tool is OK, but the handle is about 2 inches too long.</i>
• <i>The standard Pulaski is all right. It's light and might be more effective if the grubbing end was bigger. The same worker commented that the Super Pulaski is a little heavy. It might be more effective if made with a lighter metal.</i>
• <i>The Super Pulaski hurts my hands because of the weight.</i>
• <i>Super Pulaski is good to use gravity for swing.</i>

DISCUSSION

These results reflect a firefighter population of average height and weight and may not be completely applicable to firefighters over 6 feet or shorter than 5 feet 4 inches. Additionally, only one fuel type and one soil compaction were investigated.

Criteria for firefighters: six workers, each with a minimum of two years fireline experience. A random selection of tools was used by each worker. Since a minimum of two years experience was required, a learning curve was not expected to be a factor affecting performance results and kinematic measurements.

Test conditions were controlled as follows:

- The warm-up regimen was consistent and included stretching and range of motion, with and without a tool. Test workers had a 3-minute warm-up period of grubbing with each test tool, for a total of approximately 5 minutes of grubbing per tool. Consequently, analysis did not consider fatigue effects on performance.
- Delivery of instructions/training given were uniform and consistent to all workers.
- The ambient temperature variations were not significant over the test time period, so analysis did not consider the effect of temperature on performance.

-
- Data were collected for a total of 25 strikes or more. The first strike and last 3 strikes were omitted from analysis since they reflected the beginning and end of grubbing. Furthermore, during testing, data cycles were removed when workers wiped their face, stopped for a drink, or changed hands.
 - Test instrumentation was positioned to allow the workers to grub without being constrained by data collection. The sensors were mounted securely to the body part. Consequently, the sensor/body system acted as a rigid body.
 - Data was not shared with test workers until all testing was completed. This was done in order to prevent competition between test workers and between tools for each test subject.
 - The Project Leader signaled the test crew to begin gathering data without the knowledge of the test worker.

A portable backpack version of the biomechanical analysis system is in commercial development for ski professionals. This system could be used as a portable backpack test unit for field testing on the fireline. The transmitter and laptop are in the backpack. This allows testing of biomechanics on the fireline over a prolonged period to assess effects of fatigue on physiology.

Six hours of technical videotape have been collected during field testing. If a training video is developed in the future, it is recommended that this technical videotape be used for slow motion segments.

The training program was piloted with excellent preliminary results. However the training program requires further refinement for use by Type II crews. IHC crew bosses would provide valuable input on the development of this training program and could impart additional skills beyond proper

body positions and tool techniques involved in using leg and trunk muscles for the skilled use of fire hand tools, especially by Type II crews.

Results verification testing needs to be conducted, followed by field testing in several regions, and the training program refined as appropriate for Type II crews. Interagency Hotshot Crew Superintendents can identify a group of regular firefighters; and a kinematic analysis of their motions would be conducted before and after training. Train to the newly defined parameters and re-test at the new skill level. Compare the motions of the trained firefighters to the motions of skilled firefighters identified in this report. If the newly trained firefighters use motions within one standard deviation of the motions of skilled firefighters, then the training program will be considered effective. For any motions not within one standard deviation, that part of the training program should be rewritten and results verification repeated.

Bias, tradition, and attitude must be recognized in participant ranking, tool use, and selection. There is field bias towards and against certain tools. This was proven in testing. Some firefighters commented on expectations of performance via participant rankings that were in direct contrast to actual biomechanical test values. In addition, it is not unusual for bias to persist despite use of the non-traditional tool, especially if tool use was mandated.

CONCLUSIONS

From this test it can be concluded that:

The Combi tool should be the first training tool used by regular firefighters in developing skilled technique. The Combi tool should also be used to train experienced firefighters to become more efficient. In addition, the Combi tool should be designated as the first grubbing tool of choice in light flashy fuels in decomposed granite, and when fuel type and soil conditions permit. This

has been determined by low energy cost, high productivity, and safety aspects of the Combi tool, especially for the regular firefighter, as compared with the standard and Super Pulaskis. However, responses from firefighter interviews at the end of each test cycle indicated:

- The standard Pulaski was rated high by both groups for less fatigue to the hand and arms, and high for versatility and safety.
- The Combi tool was rated poor for less fatigue to the hand and arms, fair for quality of line and versatility, and high by both groups for less shock to the handle and better grip.
- The Super Pulaski was rated high for quality of line and effectiveness by both groups, but the skilled group rated it much higher overall.
- Super Pulaski ranked high for quality of line and effectiveness, and low on shock absorption of handle and poor grip.

Participant rankings for the Combi tool on effectiveness and quality of line were the lowest for all tools, indicating a strong tool bias and low field acceptability. It can be concluded that the benefits of the Combi tool have not been fully realized. Top priority should be given to a broad field implementation of the Combi tool. This tool should be included in crew tool mixes, especially for Type II crews.

Regular workers primarily used arm and shoulder muscles, and skilled workers primarily used leg and trunk muscles for grubbing with the standard and Super Pulaskis. Consequently, regular workers using the standard and Super Pulaskis are expected to fatigue much more quickly than skilled workers due to the size difference of these muscles. With the Combi tool, regular workers again used arm and shoulder muscles, but also used some leg and trunk muscles. Regular

workers are expected to fatigue quicker with the standard and Super Pulaski as compared to the Combi tool. Firefighters with a poor grip and decreased upper body strength have a greater potential for injury with the use of the Super Pulaski. Consequently, the Combi tool is the safer, more efficient tool for regular firefighters to develop their skills.

Key Biomechanical Parameters

Based on kinematic motion analysis, a determination has been made that there are several key biomechanical parameters that define significant differences in body posture, grubbing motions, productivity, energy expended, and potential for injury between skilled and regular firefighters. There is a significant correlation between both amplitude and duration of specific biomechanical parameters and skill level. The key points determined are:

Shoulder and Hand Separation Motions

With the standard Pulaski, regular workers perform the first half of shoulder and hand separation motions similar to that of a skilled worker, but draw out the second half of the motion and perform it much more slowly. These differences are much more pronounced and distributed among a greater number of the joints with the Super Pulaski. Joint angle profiles of regular and skilled workers are the most similar for use of the Combi tool when compared to the standard and Super Pulaskis.

Tool Strike Rate

The standard Pulaski has a 3-inch hoe blade. Regular workers can strike/grub 55 strikes per minute, or 165 inches per minute. Skilled workers with 75 strikes per minute can strike/grub 225 inches per minute with the standard Pulaski. Skilled workers are 36 percent more productive as determined by tool strike rate with the standard Pulaski.

The Super Pulaski has a 6.8-inch hoe blade. Regular workers can strike/grub 40 strikes per minute, or 272 inches per minute. Skilled workers can strike/grub at 75 strikes per minute, or 510 inches per minute with the Super Pulaski. Skilled workers are 88 percent more productive as determined by tool strike rate with the Super Pulaski. However, a previous fire tool study conducted by SDTDC has determined that there is a substantial increase in the energy cost to the firefighter that far exceeds this increase in production. Also, there are safety concerns with the use of some configurations of the Super Pulaski.

The Combi tool has a 4-inch serrated blade. The regular worker with 67 strikes per minute can strike/grub 268 inches per minute. The skilled worker with 86 strikes per minute can strike/grub 344 inches per minute with the Combi tool. Skilled workers are 28 percent more productive as determined by tool strike with the Combi tool. The Combi tool is the most efficient tool based on the low energy cost, high productivity, and safety, especially for the regular firefighter.

Production Rates

Using standard hand crew production rates for medium brush for a line width of 6 feet, skilled workers using the standard Pulaski can complete 75 tool strikes for every 55 by regular workers. Productivity can increase by 68 feet per hour if the whole crew was trained to the skilled level. This productivity increase is comparable to having 2 people added to a 15-person crew.

Using the Super Pulaski, skilled workers complete 75 tool strikes for every 40 strikes by a regular worker. Productivity can increase by 136 feet per hour if the whole crew was trained to the skilled level. This is comparable to having 4 people added to a 15-person crew.

Using the Combi tool, skilled workers can complete 86 tool strikes for every 67 strikes by a regular worker. Productivity can increase by 55 feet per hour if the whole crew was trained to the skilled level. This is comparable to having 2 people added to a 15-person crew.

Tool Head Impact and G Force

Tool impact and G force were substantially higher for a regular worker when compared to a skilled worker. This is partially due to the increased lift height and the increased angular velocity resulting from the extended reach of a regular worker. This extended reach causes work on the back for two reasons. First, back exertion will be required to support the motion. Secondly, the tool will be buried further into the ground causing more strain on the back to free the tool blade to complete the motion cycle.

The tool impact force for a regular worker using the standard Pulaski was 4.5 gs, or a G force of 24.0 pounds, as compared to the skilled worker with an impact of 2.7 gs, or a G force of 15 pounds. This means the regular worker pounded the ground 67 percent harder than a skilled worker with the standard Pulaski.

The tool impact force for a regular worker using the Super Pulaski was 5.3 gs, or a G force of 37 pounds as compared to the skilled worker with an impact force of 2.9 gs, or a G force of 8 pounds. This means the regular worker pounded the ground 83 percent harder than a skilled worker with the Super Pulaski.

The tool impact force for a regular worker using the Combi tool was 3.0 gs, as compared to the skilled worker tool impact force of 1.8 gs. This means the regular worker pounded the ground 67 percent harder than skilled with the standard Pulaski.

Tool Head Height

Again, as described in the previous section, an increased tool lift height is due in part to an increased arm reach, which causes increased work on the back and inefficient use of energy. An increased tool lift height is an indicator of a need for training. Tool lift height can be reduced to an optimum lift with proper training. A regular worker elevates the standard Pulaski tool head to 32 inches, 60 percent higher than a skilled worker at 20 inches.

A regular worker elevates the Super Pulaski tool head to 41 inches, 78 percent higher than a skilled worker at 23 inches. A regular worker elevates the Combi tool head to 21 inches, 75 percent higher than a skilled worker at 12 inches.

Energy Expenditure

The Combi tool has the lowest energy expenditure for the same amount of work when compared to the standard and Super Pulaski. Consequently, the Combi tool is the most efficient tool tested.

Regular workers, with a standard Pulaski, expend the same amount of energy in two cycles that is expended by a skilled worker in three cycles simply by lifting the tool head higher. As described in the previous section, an increased tool lift height is an indicator of a need for training. Regular workers using the Super Pulaski expend the same amount of energy in one cycle that is expended by skilled workers in two cycles, simply by lifting the tool head higher.

Regular workers with the Combi tool expend the same amount of energy in two cycles that is expended by skilled workers in three cycles, simply by lifting the tool head higher. Even though the cycles are the same between the standard Pulaski and Combi tool, several

differences in tool design exist that significantly affect energy expenditure. The Combi tool weighs 18 percent less than the standard Pulaski. The Combi tool is closer to being a balanced tool than the standard Pulaski because most of the weight of the Combi tool is in the handle and it has a lightweight tool head. Finally, the tool lift height is 12 inches for the skilled worker versus 20 inches on the standard Pulaski. However, this difference is offset by a longer 40-inch handle, versus a 34-inch handle for the Pulaski. Consequently, the Combi tool has the lowest energy expenditure for the same amount of work when compared to the standard and Super Pulaski.

Body Posture and Physical Fitness

With the Combi tool, body posture—at maximum lift height and tool strike—did not vary to the same level of differences between regular and skilled workers using the standard and Super Pulaskis. This indicates that the Combi tool is the easiest tool on which to use to train regular workers to become skilled users.

Firefighters can reduce the potential for carpal tunnel syndrome and injury by being physically fit for the job, using the best grubbing technique for each fire tool, taking frequent rest breaks, rotating tools across firefighters, and holding the tool with a more natural hand position with good gripping action. These techniques are especially important for Type II crews who are not typically as work-hardened as Type I IHC crews.

There are significant differences in the levels of physical fitness between regular and skilled firefighters. The time required for the 1-1/2 mile run was 40 percent higher and percent body fat was 50 percent higher in regular workers than skilled workers. These are

significant differences in levels of physical fitness that are critical to firefighter performance and the potential for accidents or injury. An appropriate minimum performance standard based on physical requirements for skilled firefighters is crucial to safety. In addition, it is important to have a reserve available for use in emergencies. These findings indicate that minimum performance standards need to be revised to a higher level of physical fitness. Specific steps for wildland firefighters to achieve and maintain fitness and work capacity are well described in the National Wildfire Coordinating Group publication "Fitness and Work Capacity."

New tool configurations need to be developed with optimal user technique design criteria to include a balanced lightweight tool head, ergonomic handle, optimum hoe blade width, and optimum handle length. Safety and production are the ultimate criteria.

There is a safety concern with the use of the Super Pulaski, as determined by analysis of key biomechanical parameters. Regular workers do not have good control and guidance of the Super Pulaski. It is lifted higher and has a greater tool head mass, contributing to increased momentum on the down stroke. Also, the non-dominant foot is in the path of the tool head. A lost time study related to fire hand tools, specifically the Super Pulaski, has not been conducted. The Super Pulaski, as currently designed, should not be used by regular workers.

The fire tool survey of the IHC network had a response rate of 75 percent. Suggestions included tool modification information, hardware, and drawings of standard, modified, and specialty fire hand tools currently in service. The high response rate indicates a high level of interest in tool design and use.

Modifications varied from crude to prototype models meeting some aspects of basic hand tool design criteria. Some of the modified tools have wide field acceptance, such as the Bosley and Rhinehart. Some modifications of the standard Pulaski are refined designs with a hoe blade width of 4.5 inches. Some of these tool modifications warrant further study with findings reported to the field. These findings are to include pros and cons of commercial and field tool modifications with associated science-based design rationale.

Type I and Type II crews, using the described training program, can readily acquire the necessary skills to use fire hand tools more effectively and safely, including using leg and trunk muscles to provide for a sustainable work rate. The proposed training program needs further refinement with the assistance of crew bosses, including hard copy and electronic computer training modules, posters, and video. Training material should be developed based on key biomechanical parameters and pacing for a sustainable workrate. Skilled firefighters are able to pace themselves in order to maintain a sustainable workrate. Skilled workers appear to use the same amount of power, regardless of the tool weight by varying the lift height according to tool weight—less lift for more given weight—and have been observed to move the position of the hands according to the weight of the tool head, closer to the tool head for increased weight. Results verification testing, with field evaluation in several regions, should be conducted to determine if the training module is effective. Verification testing is achieved by conducting a biomechanical evaluation of regular firefighters trained to the newly defined parameters and re-tested at the new skill level. A comparative analysis should be conducted between the before and after training data.

Identification of the optimum biomechanics associated with the use of the shovel and McLeod hand tools should be conducted in order to contribute to improvements in performance, with a reduction in ergonomically induced injuries. In addition, this biomechanical data can be used to conduct a quantitative dynamics and acceleration data comparative analysis between skilled and regular firefighters to determine the amounts of stress on joints. In addition, the net dynamic moments and forces of firefighters from kinematic data, body segment mass and dimension parameters, force plate ground reaction vectors, and kinematic and kinetic data can be obtained and used to understand and reduce stresses on the joints.

RECOMMENDATIONS

Based on the findings of this test:

Top priority should be given to the broad field implementation of the Combi tool, increasing field acceptance, and including the Combi tool in crew mixes, especially for Type II crews. The Combi tool should be the first training tool used by regular firefighters in developing skilled technique. The Combi tool should also be used to train experienced firefighters to become more efficient. In addition, the Combi tool should be designated as the first grubbing tool of choice in light flashy fuels in decomposed granite, and when fuel type and soil conditions permit, as determined by low energy cost, high productivity, and safety aspects of the Combi tool when compared with the standard and Super Pulaskis.

The Super Pulaski, as currently designed, should not be used by regular firefighters.

Conduct a lost time study related to fire hand tools, specifically the Super Pulaski, to identify safety issues.

Develop a training program to teach firefighters, especially Type II crews, the necessary skills to use fire hand tools more effectively and safely, including using leg and trunk muscles, the key biomechanics parameters, and pacing for a sustainable work rate. This training program would teach Type I crews to enhance efficiency. The proposed training program needs further refinement with the assistance of crew bosses, to include hard copy and electronic computer training modules, posters, and video.

Minimum performance standards for firefighters should be revised to a higher level of physical fitness and work capacity. Wildland firefighters should be encouraged to achieve and maintain fitness and work capacity as described in the National Wildfire Coordinating Group publication "Fitness and Work Capacity."

Identification of the optimum biomechanics associated with the use of the shovel and McLeod hand tools should be conducted in order to contribute to improvements in performance with a reduction in ergonomically induced injuries.

Development of new tool configurations should continue to be based on rigorous scientific methodology. The developmental focus should continue to be based on firefighter input, impact on cutting ability, tool balance, kinematics, and safety, and include field testing in a variety of fuels and soil compactions. Tool redesign should follow the Fire Tool Experimental Design Matrix and should consider:

- Balancing of all standard fire tools should be conducted, to include bringing the center of gravity in line with the handle centerline. Balancing tools may include increasing the handle length of the Pulaski,

and reducing diameter and handle length of the Combi tool. Determine the optimum blade width of the Pulaski hoe blade.

- Testing should be expanded to continue prior development study into new handle configurations and materials for increased durability and strength, incorporating new technology regarding ergonomic considerations and materials.

- Data from the SDTDC fire tool survey should be further analyzed and the findings published in a report or catalog for field distribution. Findings should include various commercially available specialty fire hand tools and the pros and cons of commercial and field tool modifications listed with associated science-based design rationale.

BIBLIOGRAPHY

References Cited

1. Chapanis, A. 1985. Some reflections on progress. In: Proceedings of the 29th Annual Meeting of the Human Factors Society, Human Factors Society. 1-8.
2. Jukkala, Art., and Sharkey, Brian J. 1988. An improved wildland firefighting hand tool. Proj. Rep. 8851-2802-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center.
3. Sicking, Lois P. 1995. Fire tool ergonomics interim report, Proj. Rep. 9551-1208-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.
4. Chung, Jeffery Y. 1995 and 1997. Personal communication. Field Support Department Head, Lawrence Berkeley National Laboratory, U.S. Department of Energy.
5. Jukkala, Art. 1997. Personal communication. Retired, USDA Forest Service, Missoula Technology and Development Center.
6. Isernhagen, Susan J. 1988. Work injury: management and prevention. Aspen Publishers, Inc. 68-69.
7. Sicking, Lois P. 1997 and 1998. Test plan for evaluating the biomechanics of fire tools. Unpublished project test plans. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.
8. Putnam, Ted. 1995. Heavy duty leather gloves, resized, improved and NFPA compliant. Proj. Rep. 9567-2332-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center.
9. Preventing illness and injury in the workplace. April 1985. Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-H-256, Chapter 7, Ergonomics and Human Factors. 128-129.
10. Johnson, Barry L. 1989. Congressional testimony. Subcommittee on Postal Personnel and Modernization Committee on Post Office and Civil Service. Washington, DC: U.S. House of Representatives, "Carpal Tunnel Syndrome, Selected References," National Institute for Occupational Safety and Health.
11. Frymoyer, J. 1985. The challenge of the lumbar spine. Abstracted. Minneapolis, MN.
12. Snook, S. 1983. Proceedings of the conference on industrial low back pain. University of Vermont.
13. Pizatella, Timothy J., Nelson, Roger M., Nestor, David E., and Jenson, Roger C. 1986. The NIOSH strategy for reducing musculoskeletal injuries. Washington, DC: National Institute for Occupational Safety and Health.
14. McMahan, Paul B., and Page, George B. 1986. An evaluation of hand tool design and method of use of railroad hand tools on back stress and performance. Rep. No. R-639. Chicago, IL: AAR Technical Center.
15. Ozkaya, Nihat., and Nordin, Margareta. 1991. Fundamentals of biomechanics, equilibrium, motion, and deformation. New York: Van Nostrand Reinhold. p.123.

-
16. Armstrong, Thomas J., Punnett, Laura, and Ketner, Philip. 1989. Subjective worker assessments of hand tools used in the automobile industry. *American Industrial Hygiene Association*. 50 (12): 639-645.
 17. Riley, M.W., Cochran, D. J., and Schanbacher, C. A. 1985. Force capability differences due to gloves. *Ergonomics*. 28:441-447.
 18. Wanj, M.J., Bishu, R.R., and Rogers, S.H. 1987. Grip strength changes when wearing three types of gloves. In: *Human Factors Interface 1987: Western New York Human Factors Society*; Rochester, N.Y.
 19. Sharkey, Brian. J. 1989. *Fatigue & the fire fighter*. NFES 2072. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center. 6-8.
 20. Sharkey, Brian. J. 1997. *Fitness and work capacity*, second edition. Tech. Rep. 9751-2814-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center. 78 p.

Additional References

The following references provided additional information. These references may be obtained from a public or university library.

Brigden, Roy. 1997. *Agricultural hand tools*. Shire Publications Ltd.

Budd, Grahame; Brotherhood, John; Hendrie, Leigh; Chaney, Phil; and Dawson, Mark. 1996. *Safe and productive bush firefighting with hand tools*. Commonwealth of Australia.

Criteria for a recommended ergonomics standard. 1989. Pub. No. 89-106. Washington, DC: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health.

Cumulative trauma disorders in the workplace. 1995. Washington, DC: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Darss-Mueller, H. 1982. *The significance of ergonomics to agroforestry*. Institute of Ergonomics of the Federal Research Center for Forestry and Forest Products. Hamberg-Reinbek.

Grood, E.S., Suntay, W.J. 1983. A joint coordinate system for the clinical description of three dimensional motions: application to the knee. *Journal of Biomechanical Engineering*, Vol. 105.136-144.

Joint Army-Navy-Air Force Steering Committee. 1972. *Human engineering guide to equipment design*, revised edition. John Wiley & Sons.

Hallman, Richard G. 1988. *Hand tools for trail work*. Pub. No. 8823-2601-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service. Missoula Technology and Development Center.

Johnson, I.M., and O'Neill, D.H. *The role of ergonomics in tropical agriculture in developing countries*. National Institute of Agriculture Engineering.

King, Barry G., and Showers, Mary Jane. 1987. Human anatomy and physiology, fifth edition. W.B.Saunders Company. 171 and 189.

Kroemer, K.H.E., Kroemer, H.J., and Kroemer-Elbert, K.E. 1990. Engineering physiology bases of human factors/ergonomics, second edition. Van Nostrand Reinhold.

Lagerlof, Elisabeth. 1979. Accidents—their causes and prevention. National Board of Occupational Safety and Health, Stockholm, Sweden.

Logan, S.F., Groszewski, P., Kreig, J.C., and Vannier, M. 1988. Upper extremity kinematics assessment using four coupled six degree of freedom sensors. Instrument Society of America. Paper number 88-0211, 0067-8856/88/075-081. St. Louis, MO: Washington University School of Medicine.

MacLeod, Dan. 1995. The ergonomics edge. Van Nostrand Reinhold.

Pearson, Jon, Hayford, John, and Royer, Wedi. 1995. Comprehensive wellness for firefighters. Van Nostrand Reinhold.

Raab, Frederick H., Blood, Ernest B, Steiner, Terry, and Jones, Herbert R. 1979. Magnetic position and orientation tracking system. IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-15, Number 5.

Radwin, Robert G., and Haney, Jonathan T. 1996. An ergonomics guide to hand tools. American Industrial Hygiene Association. Fairfax, VA.

Rodgers, Suzanne H. 1983. Ergonomic design for people at work. Volume 1, Van Nostrand Reinhold.

Rodgers, Suzanne H. Matching worker and work site-ergonomics principles.

Saunders, Mark S., and McCormick, Ernest J. 1993. Human factors in engineering and design, seventh edition. New York: McGraw Hill, Inc. 399 p.

Selan, Joseph. 1994. The advanced ergonomics manual. Advanced Ergonomics, Inc.

Sharkey, Brian J. 1989. A study of wildland firefighting work/rest cycles. Proj. Rep. 89-35-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center.

Sharkey, Brian J. 1980. Development and evaluation, muscular fitness tests. Proj. Rep. 8051-2201-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center.

Sharkey, Brian J. 1985. Fit to work. NFES 1595. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center.

Sharkey, Brian J. 1984. Physiology of fitness. Champaign, IL: Human Kinetics Publishers, Inc.

Sirosis, Al. 1967. Evaluation of fiberglass handles. Proj. Rep. 1404.1. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

United States Department of Health and Human Services. 1981. Work practices guide for manual lifting. National Institute for Occupational Safety and Health, Cincinnati, OH.

Van Loon, J.H, Staudt, F.J., and Zander, J. 1979. Ergonomics in tropical agriculture and forestry. Center for Agricultural Publishing and Documentation, Wageningen, The Netherlands.

Webb, R.D.G., and Hope, P.A. 1983. Ergonomics and skidder operations in northern Ontario. Information Report DPC-X-15, Canadian Forestry Service.

Woodson, Wesley E., Tillman, Barry, and Tillman, Peggy. 1992. Human factors design handbook, second edition. McGraw-Hill, Inc.

Woodson, Wesley E., and Conover, Donald. 1970. Human engineering guide for equipment designers, second edition. University of California Press.

APPENDIX A

Definitions

Adduction – Abduction. Adduction is movement toward the body, such as in right shoulder adduction. It occurs in the shoulder joint when a raised arm is lowered. Abduction is movement away from the body, such as in right shoulder abduction. It occurs in the shoulder joint when the arm is lowered and raised, respectively. Adduction is the opposite of abduction.

Flexion – Extension. Flexion is bending, decreasing the angle between different parts of the body. Flexion is performed at the elbow joint when the forearm is bent back on the arm. Extension is straightening the arm, increasing the angle between different parts of the body. Flexion is opposite extension.

Internal - External Rotation. Rotation is turning a body part on an axis without displacement.

Joint Angle Profile. Graph that shows how the angular position of a joint varies over the duration of the motion. Measurement of this allows a comparative analysis between different workers completing the same motion. This is important because a determination can be made of the optimum motions, presenting the opportunity to change a regular motion to a different skilled motion. Standard deviation of biomechanical values is also indicated.

Joint Angular Velocity Profile. Graph that shows how the angular speed of a joint varies over the duration of the motion. These are similar to the joint angle profile but indicate the speed of movement.

Motion Cycle Time. The time for a single complete cycle of the motion to occur, also called tool stroke rate. For example the grubbing motion starts as the firefighter begins lifting the tool head from the soil and ends the next time the head

impacts the soil. Comparing the cycle times of skilled and regular workers indicates how quickly a specific length of fireline can be constructed. However, the effectiveness of grubbing technique is not addressed by the motion time cycle.

Peak Angular Velocity. The fastest or greatest measured value of the “Joint Angular Velocity Profile”.

Posture at Maximum Tool Lift Height and Posture at Tool Impact. The positions of the body at the time of maximum elevation of the tool head from the ground, and when the tool head impacts the soil. These two positions appear to indicate significant differences in the overall motion. For example, in general the posture at maximum tool height for regular workers has the tool and arm segments much higher than those of the skilled worker. This indicates a greater work input to elevate both the tool and the arms. The posture at tool impact for regular workers is generally more out stretched than skilled workers. The out stretched posture results in greater load translated to the lower back, predisposing the worker to lower back strain.

Pronation – Supination. Pronation is turning the palm and forearm downward. Supination is the turning the palm and forearm upward.

Range of Motion. The angular range from the smallest bend angle to the greatest bend angle. For example, the knee has a range of motion from approximately 0 degrees with the knee locked, to 160 degrees with the heel nearly touching the back of the thigh. Comparing this between a regular and skilled worker provides information regarding the distance the worker traveled through the full range of motion. In the case of the range of motion for the upper extremities, some of these ranges indicate greater effort or work output.

Standard Deviation. A statistical measure of the variation of a parameter about the average for a group. This measure can be used to evaluate similarity between groups and variation between individuals of the same group. To make evaluations based on standard deviation between two groups, plots are made. Plotting average graphs for two groups with the ± 1 standard deviation bands on the same axes, allows a visual evaluation of the similarity between the two groups. If the two bands have a large overlap, the groups are similar with respect to the parameter graphed. Conversely, if the two bands show little or no overlap, the groups are dissimilar. The larger the band separation between two groups, the greater the difference between the groups. Regarding the variation of a measured value within the group, the magnitude or width of the band is examined. The wider the band, the greater variation within the group, while a smaller band indicates less variation within the group.

Tool Impact Acceleration. Defined as the rate of change of velocity of the tool and is an indirect measure of how hard the tool head hits the ground. It is dependent on tool weight and the height the tool is lifted. Firefighters grub line to bare mineral soil. This requires depth and area to clear all combustible material. Consequently, the tool blade may not need to go deeper than two inches. However, the harder the tool impacts the ground, the further the blade will penetrate into the soil. Thus, the regular worker may bury the tool further

into the ground than is necessary, burying the blade, using energy to unbury the blade, then resume productive work. This may seem trivial at first, after all, the worker has still cleared the area to bare soil. However, more soil than necessary has been removed, the blade had to be unburied; as a result, unproductive work has been done in the process.

Tool Lift Height. Tool lift height is how high up the worker raises the tool at the beginning of the stroke. It is the vertical distance from ground to the tool head. The higher the tool is lifted, the greater the amount of work done against gravity. Consequently, if a regular worker lifts the tool higher than a skilled worker, more work has been done, i.e., expended more energy. Assuming that skilled and regular workers have the same amount of energy to expend, the skilled worker could perform more grubbing cycles and thus produce a longer fireline, simply because energy was not wasted by lifting the tool too far above the ground, possibly burying the blade on impact and having to use additional energy to unbury the blade. If the tool lift height is too low, the tool may bounce off and not penetrate the surface.

Tool Head Path. The tool head path curve indicates the amount of work used for each tool stroke cycle and gives an indication as to whether the blade was buried on impact.

Ulnar/radial Deviation. The variation in position of the ulnar and radial musculo-skeletal segment.

APPENDIX B

Fire Hand Tool Test Matrix

Dependent Variables	
Performance	Muscular Fatigue
Production of Line	Posture—Back/Arm/Shoulder
Heart Rate, O2 Debt	EMG - Fatigue
	Ergonomics
	Pain/Discomfort
	Strain

Independent Variables
Accident Rates
Age
Sex/Gender
Ethnicity
Anthropometric Data
Height
Weight
Arm Length/Reach
Arm Circumference
Physiological Data
Body Mass Index/Body Fat
Hand/Grip Strength
Arm Strength
Lung Capacity/Tidal Volume
Heart Rate
Endurance
Smoking
Health
Accident History/Disability
Field Experience
Tool Training
Rest Period Intervals/Duration
Environmental Factors
Temperature
Humidity
Wind Velocity/Chill
Terrain
Vegetation
Soil Type/Soil Compaction
Clothing
Gloves
Personal Protection Equipment Attire
Footwear
Gear/Pack Weight
Psychological Factors
Motivation
Fear
Competitiveness
Attitude
Team Effort
Individual Effort
Tool Design; Tool Weight
Tool Handle Length
Hoe/Blade Width; Hoe/Blade Sharpness; Hoe/Blade Angle
Tool Aesthetics/Appearance

Test Duration (Time); Other(s); Note - Need to select and run correlation, inferential statistical analysis such as T-test, Chi-square, or Nonparametric tests, etc.

APPENDIX C
Biomechanics of Fire Hand Tools Test Matrix

Subject Data: Constants			
Initials _____	Pack Test _____	gloves _____	soil conditions _____
Age _____	Body Fat _____	terrain _____	grubbing rate _____
Gender _____	Grip Force _____	fatigue effects _____	work & rest cycle _____
# of fires fought _____	Arm Pull _____	ambient temp _____	relative humidity _____
Height _____	Arm Lift _____	wind speed _____	
Weight _____			
Hours of Training in _____		Time for 1.5 mile run _____	
Fire Hand Tool Use:			
Independent Variables	Dependent Variables		
Tool Number	Human Kinematic Values	Physiological Data Points	Tool Kinematic Data Points
1. Pulaski standard head 34.5" wood no grip 2. Pulaski Super head 34.5" wood no grip 3. Combi standard head 40" wood, no grip	Human joint linear & angular position-velocity, acceleration, deceleration (amplitude & duration), forward bend angle, shoulder and grip position; position of feet relative to fireline. Sensors placed @ right wrist/ elbow/ shoulder T3; @ left wrist/ elbow/shoulder.	Heart rate at 140 to 150 beats per minute.	Tool deceleration rate variations (amplitude& duration).

APPENDIX D
Preference Rating of Hand Tools

For each category, rank the tools you have used today.

Rate on a scale of -5 to 0 to +5

With +5 being the most, -5 being the least and 0 being no difference.

	Standard Pulaski	Super Pulaski	Combi Tool
For an equal period of use, this tool produces: More line than the other tools.			
As compared to the other tools, this tool is: A more effective tool			
As compared to the other tools, this tool is: A more versatile tool			
As compared to the other tools, this tool produces: More hand and arm fatigue			
As compared to the other tools, this tool produces: More lower back fatigue			
From an overall safety standpoint, this tool is: Easier to control and safer to use			
As compared to the other tools, this tool produces: More vibration absorption			
As compared to the other tools, this tool has: More handle grip			

APPENDIX E

Biomechanical Angle Profiles and Angular Velocity Profiles

This Appendix contains graphs and tables of biomechanical data evaluated, but not directly referenced in the data analysis section of this document.

The comparative analysis included obvious differences between skilled and regular firefighters, between the standard Pulaski, Super Pulaski and Combi Tool in:

- ✓ work cycle time (tool stroke rate)
- ✓ tool lift height
- ✓ tool impact acceleration
- ✓ tool head path
- ✓ hand separation
- ✓ posture at maximum tool lift height
- ✓ posture at tool strike/impact acceleration
- ✓ range of motion, for all joints
- ✓ peak angular velocities, for all joints
- ✓ joint angle profiles, for left and right shoulder for internal/external rotation, adduction/abduction and flexion/extension
- ✓ joint angle profiles, for left and right elbow for pronation/supination, adduction/abduction, and flexion/extension
- ✓ joint angle profiles, for left and right wrist for internal/external rotation, ulnar/radial deviation, and flexion/extension
- ✓ joint angular velocity profiles, for left and right shoulder for internal/external rotation, adduction/abduction and flexion/extension
- ✓ joint angular velocity profiles, for left and right elbow for pronation/supination, adduction/abduction, and flexion/extension
- ✓ joint angular velocity profiles, for left and right wrist for internal/external rotation, ulnar/radial deviation, and flexion/extension

These graphs and the data used to generate the graphs are not included here, but are available from the author upon request.

APPENDIX F

Table of Values

Table F1—Peak Angular Velocity and Time for all Biomechanical Parameters for the Standard Pulaski, Super Pulaski, and Combi Tool.

Table F2—Body Posture at Maximum Tool Height for all Biomechanical Parameters for the Standard Pulaski, Super Pulaski, and Combi Tool.

Table F3—Body Posture at Tool Strike for all Biomechanical Parameters for the Standard Pulaski, Super Pulaski, and Combi Tool.

Table F4—Range of Motion for all Biomechanical Parameters for the Standard Pulaski, Super Pulaski, and Combi Tool.

These tables are not included, but are available from the author upon request.

