United States
Department of
Agriculture

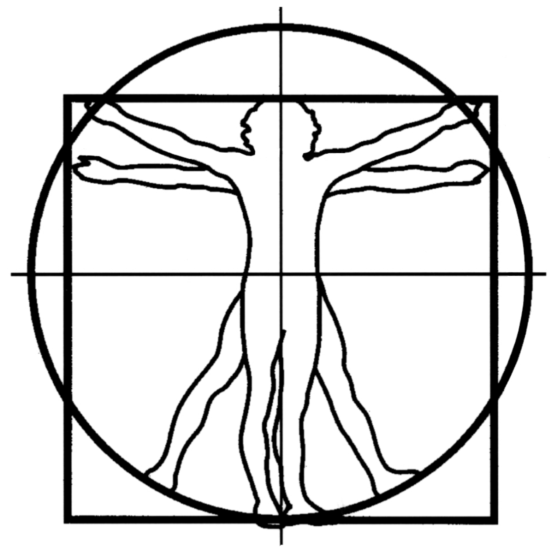
Forest Service

Technology &
Development
Program

5100—Fire Management
May 2003
0351 1204—SDTDC

Biomechanical Analysis of Grubbing Technique in the Use of Fire Handtools—A Synopsis

Biomechanical Analysis of Grubbing Technique in the Use of Fire Handtools—A Synopsis



Lois P. Sicking
Biomechanics Engineer

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

TABLE OF CONTENTS

INTRODUCTION 1

BACKGROUND 1

ERGONOMIC PRINCIPLES FOR USE IN WILDLAND FIREFIGHTING 1
- Grip Strength, Glove, and Handle Surface 2
- Fitness for Firefighters 2

CONCLUSIONS 3
- Key Biomechanical Parameters 4
- Survey Results 7
- Proposed Training Program 7

RECOMMENDATIONS 9

INTRODUCTION

Ergonomics is the study of how humans and machines work together best, thereby reducing the potential for injury, improving safety, and increasing productivity. In wildland firefighting, using ergonomic principles can prevent or minimize injuries to firefighters, enhance safety, and increase the amount of fireline. Using such principles can reduce firefighter compensation claims, increase employee retention, provide for a higher percentage of skilled firefighters, improve employee morale, and establish a safer, more productive workforce.

The body posture, motions, and tool swing techniques of 22 firefighters from 5 forests using the standard pulaski, super pulaski, and the combination (combi) tools were evaluated using a magnetic motion capture/analysis system. The tool testing was videotaped and evaluated for each firefighter's skill level. Based on this evaluation by the Interagency Hotshot Crew Superintendent and Assistant Superintendent, workers/firefighters were categorically grouped—by skill level—as either a regular or skilled firefighter.

As expected, the motions of a skilled firefighter varied significantly from those of a regular firefighter. Bend-over angle, shoulder position, grip, separation of hands, position relative to fireline, tool displacement, tool stroke rate, and tool head path varied widely.

The San Dimas Technology and Development Center (SDTDC) biomechanics engineer noticed that regular firefighters used arm and shoulder muscles primarily to power fire tools. In direct contrast, skilled firefighters used leg and trunk muscles mainly, and arm and shoulder muscles sparingly. Arm and shoulder muscles are significantly smaller than leg and trunk muscles. Regular firefighters were expected to fatigue much more quickly due to the size difference of these muscles. Consequently, it is important to describe in detail the body posture, motions, and tool swing techniques of skilled firefighters using primarily leg and trunk muscles for grubbing. This study provided an opportunity to capture and use the knowledge of veteran firefighters to train new and less experienced firefighters.

BACKGROUND

SDTDC has conducted several fire handtool studies, including a fire tool survey of firefighters regarding specialty fire tools, modified fire tools, and fiberglass handles. The survey also included questions about how balanced fire tools are and how various widths of the pulaski hoe blade affected construction of a fireline.

Data analysis from a previous fire tool study conducted by the SDTDC biomechanics engineer indicated that the greatest improvement in safety and fireline production, especially for Type II crews, could come from training these crews to achieve the best grubbing technique with the standard and super pulaskis and the combination (combi) tool. The biomechanics engineer made recommendations for determining the optimum grubbing technique and for developing a training program both to teach regular firefighters how best to use fire handtools and to provide a review for skilled firefighters. The engineer developed a preliminary training program that is described in the Tech Tips, 0251-1302-SDTDC.

ERGONOMIC PRINCIPLES FOR USE IN WILDLAND FIREFIGHTING

Low back pain and carpal tunnel syndrome were the two most common firefighter health concerns commented on in the earlier SDTDC fire tool survey. These conditions are best evaluated by a detailed motion analysis. Factors related to these two health conditions are the level of physical fitness, abdominal muscle strength, and trunk muscle balance and the incidence of repetitive heavy lifting, bending, twisting, awkward postures, fatigue, emotional stress, and even cigarette smoking. Other important ergonomic considerations are type and design of gloves, amount of handgrip strength, and how to achieve and maintain the level of physical fitness necessary for wildland firefighters.

Grip Strength, Gloves, and Handle Surface

Firefighters make an effort to increase grip strength by turning gloves inside out, exposing the glove seams to increase the glove surface area making contact with the tool handle. In addition, some Interagency Hotshot Crew (IHC) firefighters buy “structure” type gloves with personal funds. These gloves have a rough outside surface, thinner seams, and no seams in the palm; all aspects that increase grip strength. Structure gloves typically extend at least 4 inches past the wrist, important in preventing embers, dirt, and debris from getting into the gloves. Gloves with seams between the fingers and on the palm interfere with grip development. Thick gloves with seams can reduce grip strength up to 40 percent.

Decreased grip strength results in incidents of dropped tools, poor tool control, low work quality, and increased fatigue. Some IHCs roughen the tool handle surface by removing handle varnish, increasing the friction value to enhance gripping action.

Fitness for Firefighters

Fitness is the most important factor in predicting the ability to build fireline at a sustainable work rate without experiencing undue fatigue or creating a safety hazard for yourself or other firefighters. Many Federal and State agencies have used the step test to predict aerobic fitness. Fitness cannot be rushed. Achieving fitness is a gradual process that may require an exercise program of 6 weeks or more. Firefighters are wise to train for physical fitness before the fire season begins, not while on the fireline. See the National Wildfire Coordinating Group publication, “Fitness and Work Capacity,” for guidance on achieving and maintaining physical fitness for firefighters.

CONCLUSIONS

Based on the biomechanics testing, the combi tool was superior to the standard and super pulaski in regard to safety aspects, low energy cost, and high productivity, especially for the regular firefighter. The combi tool should be the first tool used to train regular firefighters in developing skilled grubbing technique and in becoming more efficient. The combi tool should also be designated as the best grubbing tool in light flashy fuels and whenever fuel type and soil conditions permit.

Participants ranked the combi tool effectiveness and quality of line as the lowest for all tools, indicating a strong tool bias and low field acceptability. The benefits of the combi tool have not been fully realized. The fire community should give top priority to a broad field implementation of the combi tool and include it in crew tool mixes, especially for Type II crews. See table 1.

Table 1. 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 biomechanics test results show that regular firefighters used different muscle sets while grubbing with the test tools compared to skilled firefighters. Skilled firefighters primarily used leg and trunk muscles with the standard and super pulaski, while regular firefighters primarily used the smaller arm and shoulder muscles. Due to the size difference of these muscle sets, regular firefighters using the standard and super pulaski are expected to fatigue faster than skilled firefighters.

Regular firefighters using the combi tool employed less of the smaller arm and shoulder muscles and more of the larger leg and trunk muscles. Consequently, regular firefighters are not expected to fatigue as quickly using the combi tool because large leg and trunk muscles are used. Regular firefighters are expected to fatigue more quickly using the standard and super pulaski because they primarily use their smaller arm and shoulder muscles compared to use of the combi tool, where more large leg and trunk muscles were used.

Use of the super pulaski also increases the potential for injury for firefighters with a poor grip and decreased upper body strength. The combi tool is the safer, more efficient tool for regular firefighters to develop their skills.

Key Biomechanical Parameters

Overall, skilled firefighters generated smooth, consistent motions, regardless of body size or gender. Conversely, the regular firefighters had more variation in body posture and tool swing motions. Key differences between skilled and regular firefighters in body posture, grubbing motions, productivity, energy expended, and potential for injury are best described by the following:

Energy expenditure—Compared to the standard and super pulaski, the combi tool has the lowest energy expenditure for the same amount of work. Consequently, the combi tool is the most efficient tool tested.

Regular firefighters using a standard pulaski or a combi tool expend the same amount of energy in two cycles that a skilled firefighter expends in three cycles simply by lifting the tool head higher. Regular firefighters using the super pulaski expend the same amount of energy in one cycle as a skilled firefighter expends in two cycles simply by lifting the tool head higher. This difference in motion cycles and tool lift height between regular and skilled firefighters indicates a need for training.

Even though the cycles are the same between the standard pulaski and the combi tool, several differences in tool design significantly affect energy expenditure. The combi tool weighs 18 percent less than the standard pulaski and is a more balanced tool. It has a lightweight tool head and most of its weight in the handle, unlike the pulaski. The combi tool lift height is 12 inches for the skilled firefighter versus 20 inches for the standard pulaski. This small lift height is further offset by a 40-inch-long combi tool handle versus a handle of 34 inches for the pulaski. Consequently, the combi tool has the lowest energy expenditure for the same amount of work as compared to the standard and super pulaski.

Body posture—When regular and skilled firefighters used the combi tool, their body posture at maximum lift height and tool strike did not vary as significantly as when they used the standard and super pulaski. This indicates that the combi tool should be the easiest tool for training regular firefighters to become skilled firefighters.

Crew production rates—Based on standard hand crew production rates for medium brush for a line width of 6 feet, skilled firefighters can complete 75 tool strikes for every 55 by a regular firefighter using the standard pulaski. If the whole crew was trained to the skilled level, productivity could increase by 68 feet per hour. That is comparable to having 2 people added to a 15-person crew.

With the super pulaski, skilled firefighters complete 75 tool strikes for every 40 by a regular firefighter. If the whole crew was trained to the skilled level, productivity could increase by 136 feet per hour. That is comparable to having 4 people added to a 15-person crew.

With the combi tool, skilled firefighters can complete 86 tool strikes for every 67 by a regular firefighter. If the whole crew was trained to the skilled level, productivity could increase by 55 feet per hour. That is comparable to having 2 people added to a 15-person crew.

Tool-Head Impact—Tool-head impact force was substantially higher for regular firefighters than for skilled firefighters. The regular firefighters increased lift height and extended reach contributed to the tool-head impact force and could cause back injury. Increased lift height requires back exertion. Because of the angular velocity caused by the extended reach, the tool is buried further in the ground. Freeing a tool blade that is buried further in the ground and completing the motion cycle causes strain on the back.

The tool impact force for a regular firefighter using the standard pulaski was 4.5 g, compared to the skilled firefighter with an impact force of 2.7 g. This means the regular firefighter pounded the ground 67 percent harder than a skilled firefighter with the standard pulaski. The tool impact force for a regular firefighter using the super pulaski was 5.3 g, compared to the skilled firefighter with an impact force of 2.9 g. Therefore, the regular firefighter pounded the ground 83 percent harder than a skilled firefighter with the super pulaski. The tool impact force for a regular firefighter using the combi tool was 3.0 g, compared to the skilled firefighter tool impact force of 1.8 g. This means the regular firefighter pounded the ground 67 percent harder than the skilled firefighter with the standard pulaski. See figure 1.

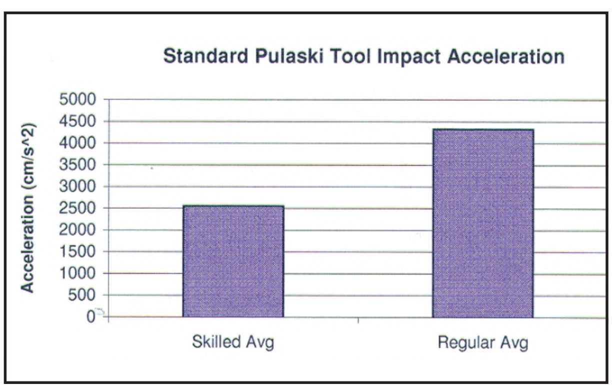


Figure 1—Tool impact force or acceleration comparison of skilled versus regular firefighters with the standard pulaski.

Tool-Head Height—As described in the previous section, an increased tool lift height is due in part to an increased arm reach, causing increased work on the back and inefficient use of energy. Tool lift height can be reduced to an optimum lift with proper training. A regular firefighter elevates the standard pulaski tool head to 32 inches, 60 percent higher than a skilled firefighter at 20 inches. See figure 2. A regular firefighter elevates the super pulaski tool head to 41 inches, 78 percent higher than a skilled firefighter at 23 inches. A regular firefighter elevates the combi tool head to 21 inches, 75 percent higher than a skilled firefighter at 12 inches.

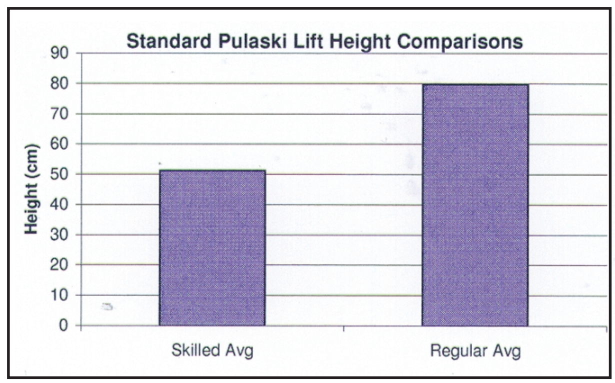


Figure 2—Tool lift height comparison of skilled versus regular firefighters with the standard pulaski.

Tool Strike Rate—The standard pulaski has a 3-inch hoe blade. The regular firefighter can strike or grub 55 strikes per minute, or 165 inches per minute. With 75 strikes per minute, the skilled firefighter can strike or grub 225 inches per minute using the standard pulaski. Skilled firefighters are 36 percent more productive as determined by tool strike rate with the standard pulaski. See figure 3.

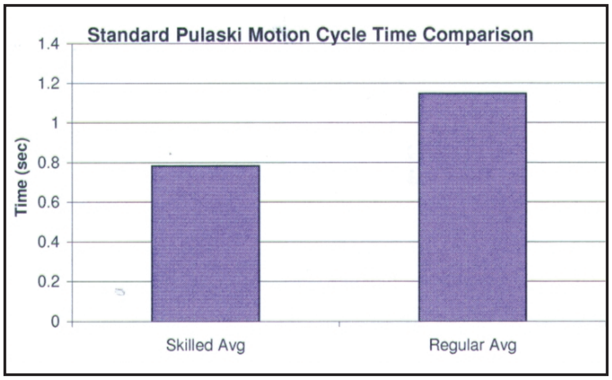


Figure 3—Tool motion cycle or stoke/strike rate comparison of skilled versus regular firefighters with the standard pulaski.

The super pulaski used in this study had a 6.8-inch hoe blade. The regular firefighter can grub 40 strikes per minute or 272 inches per minute. The skilled firefighter can grub 75 strikes per minute or 510 inches per minute with the super pulaski. Skilled firefighters are 88 percent more productive as determined by tool strike rate with the super pulaski. However, a previous SDTDC fire tool study demonstrated that the substantial increase in energy cost to the firefighter far exceeds the production increase. In addition, use of some configurations of the super pulaski have raised safety concerns.

The combi tool has a 4-inch serrated blade. With 67 strikes per minute, the regular firefighter can strike 268 inches per minute. With 86 strikes per minute, the skilled firefighter can strike 344 inches per minute with the combi tool. Skilled firefighters 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.

Physical Fitness—Significant differences in levels of physical fitness exist between regular and skilled firefighters. The time required for the 1½-mile run was 40 percent higher and percent body fat was 50 percent higher in regular firefighters compared to skilled firefighters. This indicates a substantially lower level of physical fitness, which is critical to firefighter performance and increases 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 physical fitness capacity 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 clearly described in the National Wildfire Coordinating Group publication, “Fitness and Work Capacity.”

Firefighters can reduce the potential for carpal tunnel syndrome and other injuries 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 tools with a more natural hand position for good gripping action. These are especially important for Type II crews who are typically less work-hardened than Type I IHC crews.

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

Safety—Analysis of key biomechanical parameters with the use of the super pulaski identified a significant safety concern. Regular firefighters lack 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 downstroke with the nondominant foot in the tool head path. Lost time studies related to fire handtools, specifically the super pulaski, have not been conducted. Regular firefighters should be discouraged from using the super pulaski model with a 6.8-inch blade width until the proper training and minimum physical standards, including grip and upper body strength, have been defined and implemented to address the increased angular acceleration and twist on impact. Exercises with a handspring device can increase grip strength.

Survey Results

The fire tool survey of the IHC network had a response rate of 75 percent, with submission of tool modification information, including hardware and drawings of standard, modified, and specialty fire handtools in service. The response indicates a high level of interest in tool design and use. Modifications varied from crude to prototype models that met some aspects of basic handtool 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. The report of findings to the field should include pros and cons of commercial and field tool modifications with associated science-based design rationale.

Proposed Training Program

By using the proposed training program described in Tech Tips 0251-1302-SDTDC, Type I and II crews can readily acquire the necessary skills to use fire handtools more effectively and safely, including the primary use of leg and trunk muscles to provide a sustainable work rate. This training program was developed to implement the five principle factors of skilled grubbing and the primary use of leg and trunk muscles, including tool lift height, work cycle time (stroke rate), hand separation, right shoulder angle, and position of the feet. See figures 4a and 4b.

The proposed training program needs further refinement with the assistance of crew bosses, to include printed and electronic computer training modules, posters, and videos. Training material based on key biomechanical parameters and pacing for a sustainable work rate needs to be developed. Skilled firefighters pace themselves to maintain a sustainable work rate. They appear to use the same amount of power by varying lift height according to tool weight, exercising less lift for more given weight, and compensating for tool head weight by positioning the hands more closely to the tool head as weight increases. The SDTDC biomechanics staff should conduct results verification testing with field evaluation in several regions to determine whether the training module is effective.

REGULAR WORKERS

- Position the nondominant foot slightly forward and intersecting the tool path.
- Flex the knees and may or may not keep the back straight.
- Stand more upright, bent at the waist but the back is not parallel to the ground.
- Move the back in a bobbing motion and use arm and shoulder muscles for grubbing.
- Angle the tool blade towards the nondominant foot in the tool swing path. Stop the tool swing short of the foot.
- May use an increased arm reach to compensate for the difference in body posture relative to the fireline.

SKILLED WORKERS

- Have the dominant foot slightly forward and essentially parallel to the tool path; the nondominant foot is 60 degrees off the dominant foot.
- Flex knees and keep the back straight, bent at the waist at an angle almost parallel to the ground.
- Keep the tool blade angled away from the body, with feet positioned out of the way of the swing of the tool blade.
- Keep the back position almost steady during the tool swing.
- Use leg and trunk muscles for grubbing.

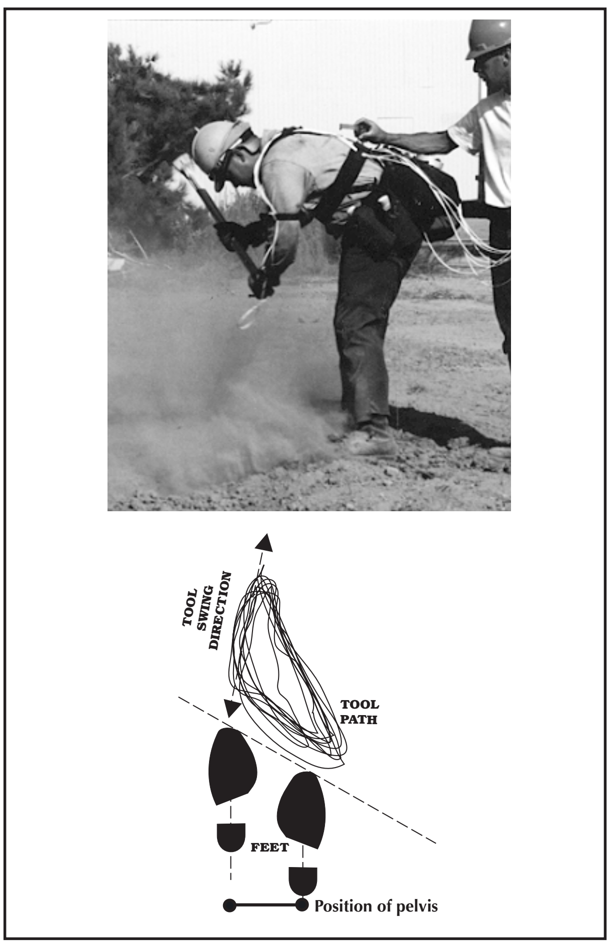


Figure 4a—Regular firefighter body posture and tool swing path.

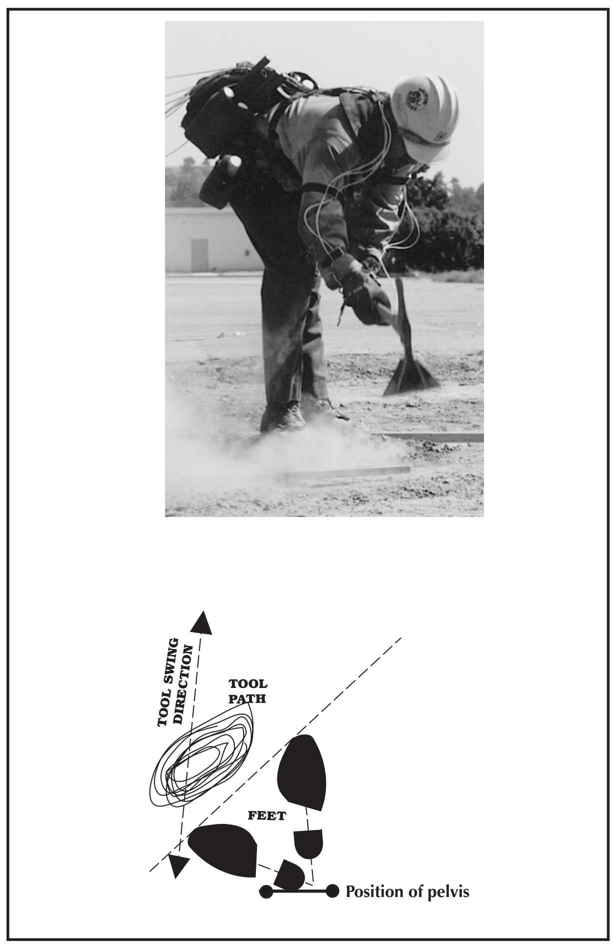


Figure 4b—Skilled firefighter body posture and tool swing path.

For verification testing, the SDTDC biomechanics staff should conduct a biomechanical evaluation of regular firefighters trained to the newly defined parameters and retest the firefighters at the new skill level. A comparative analysis would be conducted between the before-and-after training data.

To improve performance with an expected corresponding reduction in ergonomically induced injuries, the SDTDC biomechanics staff should identify optimum biomechanics associated with the use of the shovel and McLeod handtools. This biomechanical data can be used to conduct a quantitative dynamics and acceleration data comparative analysis between skilled and regular firefighters to determine the amount of stress on joints. Measuring and understanding 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 also help in developing techniques to reduce stress on joints.

RECOMMENDATIONS

The following recommendations were developed based on the conclusions:

- Give top priority 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. Use the combi tool as the first training tool for regular firefighters in developing a skilled technique and in training experienced firefighters to become more efficient. In addition, designate the combi tool as the preferred grubbing tool in light flashy fuels in decomposed granite and when fuel type and soil conditions permit as determined by the low-energy cost, high productivity, and safety aspects of the combi tool when compared to the standard and super pulaskis.
- Discourage regular firefighters from using the super pulaski model with a 6-inch or greater hoe blade width until appropriate minimum physical standards, including grip and upper body strength, have been defined and implemented. Conduct a lost time study related to fire handtools, 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 handtools more effectively and safely, incorporating the primary use of leg and trunk muscles, key biomechanics parameters, and pacing for a sustainable work rate. This training program could also teach Type I crews to improve efficiency. Refine the proposed training program with the assistance of crew bosses, including hard copy and electronic computer training modules, posters, and videos.
- Revise minimum performance standards for firefighters to establish a higher level of physical fitness and work capacity. Encourage wildland firefighters to achieve and maintain fitness and work capacity as described in the National Wildfire Coordinating Group publication, “Fitness and Work Capacity.”
- Identify the optimum biomechanics associated with the use of the shovel and McLeod handtools in order to improve performance, with an expected corresponding reduction in ergonomically induced injuries.

- Develop new tool configurations based on rigorous scientific methodology, firefighter input, cutting ability, tool balance, kinematics, and safety. Field-test the handtools in a variety of fuels and soil compactions. Redesign tools to follow the fire tool experimental design matrix.
- Establish a balanced configuration of all standard fire tools, including bringing the center of gravity in line with the handle centerline. Balancing of tools may include increasing the handle length of the pulaski and reducing the diameter and handle length of the combi tool, as appropriate. Determine the optimum width of the pulaski hoe blade.
- Further analyze data from the SDTDC fire tool survey and publish the findings in a report or catalog for field distribution. Include various commercially available specialty fire handtools and the pros and cons of commercial and field tool modifications listed with associated science-based design rationale in the report.

For further information, contact the fire program leader by phone at 909–599–1267 or by e-mail at mailroom_wo_sdtdc@fs.fed.us.