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Thumb Force and Muscle Loads Are Influenced by the Design of a Mechanical Pipette and by Pipetting Tasks

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Work involving pipetting is associated with elevated rates of musculoskeletal disorders of the hand and wrist. The purpose of this study was to quantify thumb loading and muscle activity and determine if they varied among pipetting tasks. Fourteen experienced participants performed nine pipetting tasks while surface electromyography was measured for the extensor pollicis brevis, abductor pollicis longus, flexor pollicis longus, and abductor pollicis brevis muscles. For five tasks, participants used a pipette instrumented to measure the thumb force applied to the plunger. High-precision tasks significantly increased static muscle activity but reduced peak thumb force on average 5% as compared with low-precision tasks. Pipetting high-viscosity fluids increased peak thumb forces on average 11% as compared with pipetting low-viscosity fluids. Use of a latch pipette increased muscle activity of three muscles. We conclude that pipette design and pipetting tasks can influence applied thumb force and muscle activity. We recommend that pipettes be designed to limit applied peak forces and that pipette users be instructed in use patterns that will reduce applied forces. Actual or potential applications of this research include modifications to pipette designs and worker training in order to reduce hand pain associated with pipetting.

INTRODUCTION

The plunger-operated mechanical pipette, which allows users to transfer precise volumes of liquid between containers, is one of the most commonly used hand tools in the laboratory. Use of the pipette often requires careful and precise control, which can be affected by discomfort, pain, or other musculoskeletal disorders. Bjorksten, Almby, and Jansson (1994) compared 128 Swedish female laboratory employees with 25,378 Swedish female state employees. They found an increased risk of hand (odds ratio = 5.0) and shoulder (odds ratio = 2.4) ailments associated with pipetting for more than 300 hr per year. The average amount of pipette work for laboratory technicians was 495 hr per year. Based on a survey of 80 pipette users (David & Buckle, 1997), 90% of users who pipetted continuously for more than 60 min reported hand complaints. Plunger operation and tip ejection were identified as features that made pipette operation difficult. Use of the pipette involves several risk factors associated with upper extremity musculoskeletal disorders, including repetition, force, and posture (National Research Council and Institute of Medicine, 2001). Fredriksson (1995) measured the force required to operate a pipette as a percentage of the maximum force with which participants could press on a pipette. She found that for female employees the peak force required to operate the pipette was 18.4% of maximum force, whereas for male employees it was 14.5% of maximum force.

Few studies have investigated the force applied to a manual pipette and the role of thumb muscles during pipetting, and no study, to our knowledge, has investigated how latch pipettes affect thumb muscle activity. The purpose of this study is to quantify thumb loading and muscle activity and determine whether they vary between common pipetting tasks. Although

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pipetting in general involves a high level of precision, some pipetting tasks require more precision than others. Several studies have demonstrated that the precision and attention required to complete a task can influence the level of muscle activity (Milerad & Ericson, 1994; Visser, Looze, Graaff, & van Dieen, 2004). This study will also investigate how latch pipettes, which are designed to reduce thumb activity, affect muscle activity. We hypothesize that high-precision pipetting tasks will involve greater muscle activity of the stabilizing muscles and an increase in duty cycle, that pipetting high-viscosity fluids will increase the thumb force applied to the plunger, and that use of a latch pipette will lower the muscle activity of the muscles that move the thumb.

METHODS

In this laboratory study, participants completed nine pipetting tasks while the thumb force and muscle activity were measured.

Participants

Fourteen participants (9 men and 5 women) were recruited to the study. Their mean age was 34 years (*SD* = 7.8). All participants were experienced with the use of pipettes (7.4 years, *SD* = 5.9) and worked in jobs that involved an average of 5.5 hr (*SD* = 4.8) of pipette use per week. All participants used pipettes with their right hand. Five of the participants reported previously having discomfort in the right arm, wrist, or thumb during pipetting but were pain free at the time of the study. The study was approved by the University of California at San Francisco Committee on Human Research.

Electromyography

Surface electromyography (EMG) bipolar recordings were obtained using circular Ag/AgCl electrodes with an active diameter of 8 mm and a center-to-center distance of 21 mm. Sites on the right forearm for the placement of the electrodes were localized with the forearm in a pipetting posture, using recommended anatomical placement (Delagi, Perotto, Iazzettim, & Morrison, 1981). Four thumb movers, muscles that create torque and articulate the joints of the thumb, were studied. These were the extensor pollicis brevis (EPB), abductor pollicis longus (APL), flexor pollicis longus (FPL), and abductor pollicis brevis (APB). The skin was abraded and cleaned with an alcohol pad and shaved if necessary. A ground electrode was placed over the lateral epicondyle. The EMG signals were amplified with preamplifiers and an adjustable gain amplifier and were high-pass filtered at 75 Hz (Therapeutics Unlimited, Iowa City, IA) in order to reduce 60-Hz noise.

Maximum and Reference Voluntary Electrical Activity

Both maximum voluntary electrical activity (MVE) and reference voluntary electrical activity (RVE) were obtained during isometric maximum voluntary contraction (MVC) and isometric reference voluntary contraction (RVC), respectively. Three MVC tasks were performed to generate the MVEs of the four muscles. For the EPB and APL muscles, with the hand in a “pipetting posture” the thumb is radially abducted against a static load placed on the midpoint of the first metacarpal on the dorsal side. For the APB muscle, a static load was placed over the volar aspect of the proximal phalanx of the thumb at the midpoint, and participants palmar abducted the thumb. For the FPL muscle, participants gripped a 20-cm long, 2.5-cm diameter rod with a load cell (Greenleaf Medical Systems, Palo Alto, CA) attached to the top in a posture similar to that of pipetting. The load cell was located under the palmar aspect of the distal phalanx of the thumb, and participants were instructed to press down with their thumb on the load cell as hard as they could.

To generate RVE, participants pressed on the load cell with the voltage readout displayed to them on an oscilloscope. Participants were instructed to maintain the readout at 1.5 V, which corresponded to 35.4 N; 35 N was near the maximum thumb load recorded during pipette use in pilot testing. Recordings were collected for 6 s. MVE was calculated as the maximum root mean square (RMS; 1-s smoothing window) amplitude over the 6 s. RVE was calculated as the average RMS (1 s smoothing) over the 3rd and 4th s of the task.

Pipettes

Two pipettes were used in the study, an instrumented pipette and a latch pipette. The instrumented pipette was constructed from a 1000-µl pipette (P-1000 Gilson Pipetman, Rainin, Emeryville, CA). This pipette relies on a thumb-actuated plunger to extract and dispense the liquid as well as eject the disposable tip. The process of frequently repeated thumb plunger tasks can be divided into seven steps: press plunger, hold (insert tip in sample), release plunger (aspirate), rest (locate target), press plunger (dispense and blow out), release plunger, and locate next sample.

Aspiration first requires the user to press the plunger until a tactile "stop" is reached. Figure 1, the force displacement curve of a typical pipette, illustrates this stop point, where the force required to press the plunger increases at Point A. The distance to this stop determines the volume to be collected. Next, the user must place the pipette tip into the liquid while holding the plunger down. The user slowly releases the plunger to aspirate fluid and then locates the target into which to dispense the fluid while resting the thumb on the plunger. Next, the user depresses the plunger again to the stop to dispense the fluid and applies force beyond this stop (Point A) to blow out any residual liquid. The user then releases the plunger and may rest the thumb on the top of the plunger before moving to the next sample. Each cycle may also include the loading and ejecting of a pipette tip. Tip ejection usually involves pressing a different button with the thumb.

A load cell (Entran ELF-TC-500-20, Fairfield, NJ) was modified to fit between the plunger and aspiration spring inside the pipette to measure plunger force exerted by the participant. The output was amplified (Entran IMV-15/15/100A-WW, Fairfield, NJ) and recorded on a personal computer. The instrumented pipette required 8.7 N to reach the first stop and between 20 and 35 N for blowout (Figure 1). Because of the design of the pipette, the load cell began to record applied force only when plunger forces exceeded 5 N. The instrumentation did not interfere with the normal operation of the pipette.

The second pipette was a 1000-µl latch pipette (P-1000 Rainin Pipette Plus, Rainin, Emeryville, CA). No modifications were made to this pipette. The latch pipette reduces the thumb activity to four steps in a cycle: rest (locate sample), latch release (aspirate), rest (locate target), and dispense. Beginning with the plunger already depressed at the end of the previous cycle, the user locates the sample while resting the thumb on the plunger. The magnetic latch holds the plunger down automatically. Next, the user releases the latch by pressing a button on the front of the pipette with the index finger, causing the plunger to rise automatically at a preset rate

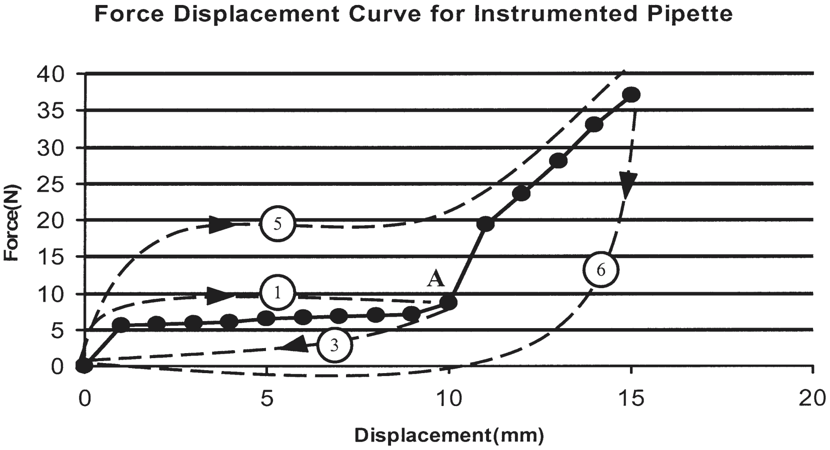

Figure 1. Static force displacement curve for the plunger of the instrumented pipette. The arrows indicate the direction of movement of the plunger. Step 1 involves pressing the plunger until a tactile "stop" is reached (Point A). At Step 3 the plunger is released in order to aspirate the fluid. Step 5 is dispensing and blowing out the fluid, generally done in one single motion; the endpoint for displacement can be anywhere between 11 and 16 mm. In Step 6 the plunger is released. Steps 2, 4, and 7 do not involve motion of the plunger.

for aspiration. The user locates the target while the thumb rests on the plunger and then depresses the plunger to dispense the liquid. The plunger is held down by the latch and remains depressed as the next cycle starts.

Pipetting Tasks

Each participant performed nine different tasks (Table 1). Tasks 1 through 4 were chosen in order to compare the effects of precision and viscosity. Tasks 5 and 6 allowed the comparison of a latch pipette with a common pipette. Tasks 7, 8, and 9 were included to obtain information about muscle activity during common tasks related to pipetting. Participants completed 10 cycles for each task (e.g., for fluid transfer, one cycle involved collecting and dispensing one sample) and were instructed to do pipetting at a pace similar to that of their usual work. Tasks were performed on a 76-cm high work surface, and the chair was adjusted to the participant's anthropometry. Participants were trained and practiced using an uninstrumented pipette until they were comfortable with each task. Two trials (10 cycles each) were completed for each task. All tasks were performed with the instrumented pipette unless otherwise indicated in the table. The order in which the tasks were performed was randomized.

Data Collection

During each trial, data collection was initiated at some point after the participant had begun the task and lasted 18 s. Participants were unaware of when data collection began. EMG and force data were recorded on a personal computer using a 12-bit A/D converter and Labview V4 software (National Instruments, Austin, TX) at a sampling rate of 3072 Hz. EMG data were rectified using an RMS conversion with a 50-ms

TABLE 1: The Pipetting Tasks Performed by Each Participant

Task Description	Task
1. Low precision/low viscosity (LP/LV)	Transfer 100 μl of water from a 50-ml centrifuge tube into a 15-ml centrifuge tube.
2. High precision/low viscosity (HP/LV)	Transfer 100 μl of yellow dyed water from a 1.5-ml microcentrifuge tubes with 500 μl of EMG gel in bottom and 500 μl of dyed water on top into 96-well plate. Users were instructed to avoid transferring any gel.
3. Low precision/high viscosity (LP/HV)	Transfer 100 μl of olive oil from a 50-ml centrifuge tube into a 15-ml centrifuge tube.
4. High precision/high viscosity (HP/HV)	Transfer 100 μl of olive oil from a 1.5-ml microcentrifuge tube with 500 μl of water in bottom and 500 μl of olive oil on top into 96-well plate filled with dyed water. Users were instructed to avoid transferring any water.
5. Repeat 1 with latch pipette (Latch 1)	
6. Repeat 2 with latch pipette (Latch 2)	
7. Tip ejection (TE)	Attach tip from tip case onto pipette, then eject. Repeat 5 times.
8. Mix	Transfer 100 μl of blue water from 1.5-ml microcentrifuge tube to a second 1.5-ml microcentrifuge tube with 200 μl of yellow water. Pump pipette 5 times to mix fluids.
9. Volume adjustment (VA)	Adjust a pipette from 200 μl to 20 μl to 200 μl by turning the volume adjustment dial.

Note. The 50- and 15-ml tubes have large diameters (26.75 and 14.75 mm, respectively), making it easy to transfer fluid between the two. The 1.5-ml tubes have small openings (8.75 mm), and the two-layer fluid increased the attention and precision required to position the pipette tip as well as the rate of aspiration in order to withdraw only one fluid. The 96-well plate is an array of 8 × 12 wells, each 6.6 mm in diameter, spaced by 2.25 mm.

time window for pipetting tasks and a 1-s time window for MVC and RVC tasks. Force data were smoothed using a 50-ms moving average.

Data Analysis

After normalization of the RMS EMG signals to the appropriate MVE and RVE, amplitude probability distribution function (APDF) levels of 10% (static activity), 50% (median activity), and 90% (peak activity) were calculated (Jonsson, 1982). APDF levels of 50% and 95% were calculated from the force data. APDF 10% levels were not calculated, given that these values would be misleading because the load cell did not record loads below 5 N. APDF 95% levels were calculated for the force measures instead of 90% because the load cell recordings contained less noise than did electromyography and APDF 95% better represents the peak loads applied to the pipette. Mean cycle time was calculated from the force measurements for each trial of Tasks 1 through 4. A cycle was defined as including two increases in the force representing press (before aspiration) and dispense/blow out (Figure 2). Duty cycle was calculated as the percentage of time of a cycle that the plunger force was greater than 6 N. APDF, mean cycle time, duty cycle, and force levels were averaged across the two trials. Differences in muscle activity and thumb force between Tasks 1 through 4 and Tasks 1, 2, 5, and 6 were separately evaluated with a repeated measures analysis of variance. Statistical analysis was performed with SAS System for Windows V8 software (Cary, NC). All error terms are expressed as standard deviations unless otherwise indicated.

RESULTS

The mean MVC thumb force was 101.3 N (±27.8). The mean RVC force was 35.3 N (±2.5), which was 34.8% (±2.5) of MVC. The mean between-participant coefficient of variation (*CV*= *SD*/mean) across all muscle activity levels and tasks after normalization to MVE was 63%, whereas the CV after normalization to RVE was 58%. EMG results are expressed as a percentage of RVE unless otherwise indicated.

Mean cycle time was lowest for Task 1 (4.46 ± 0.97 s), followed by Task 2 (5.54 ± 1.74 s), Task 4 (6.55 ± 2.23 s) and Task 3 (6.76 ± 2.31 s). Duty cycles were 52% (±7%), 54% (±9%), 50% (±8%), and 55% (±9%) for Tasks 1 through 4, respectively. Mean cycle time was significantly increased with the high-viscosity task, whereas duty cycle was significantly increased with the high-precision task.

The thumb force applied to the plunger was influenced by task (Figure 3). Higher fluid viscosity (Tasks 3 and 4) increased peak plunger

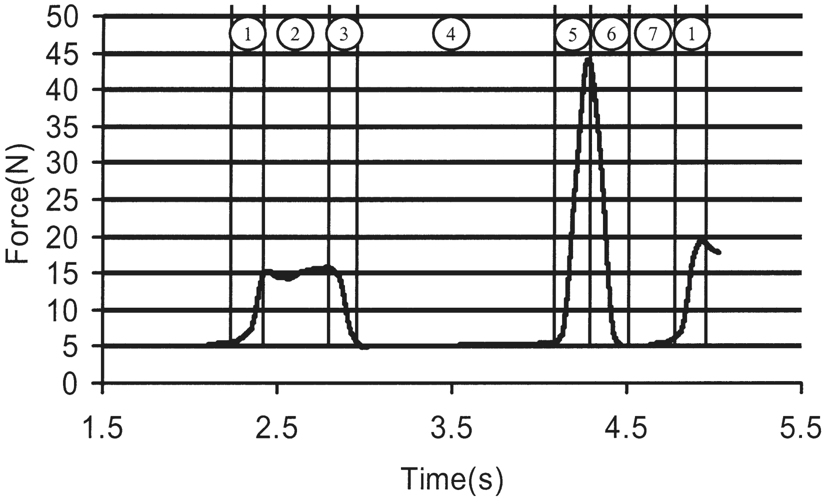

Figure 2. Typical profile during one cycle of pipetting. The numbers indicate the various phases of a pipetting cycle: (1) press plunger, (2) hold, (3) release (aspirate), (4) locate target, (5) dispense and blow out, (6) release, and (7) locate next sample.

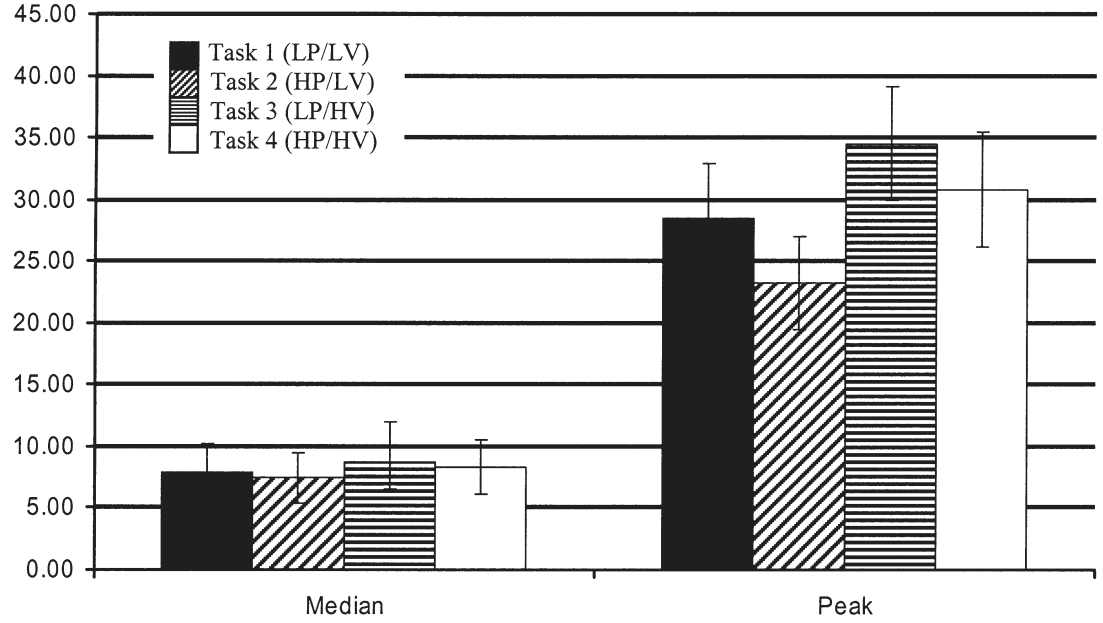

Figure 3. Chart of median (APDF 50%) and peak (APDF 95%) thumb force applied to plunger during Tasks 1 through 4 (*N* = 14). Error bars represent 1 *SEM.*

force (APDF 95%), whereas higher task precision (Tasks 2 and 4) decreased peak plunger force (APDF 95%). There was no effect of task on median (APDF 50%) thumb force. Table 2 summarizes the significant differences in muscle activity and plunger force attributable to task precision, fluid viscosity, and pipette type.

High precision was associated with an increase in static activity (APDF 10%) for each of the muscles. It also increased median activity of the EPB and APL (APDF 50%) as well as the peak activity of the EPB (APDF 90%). Fluid viscosity did not significantly affect activity of any of the four muscles (Table 2). Figure 4 displays the mean APDF 10%, 50%, and 90% muscle activity level for each of the four muscles for Tasks 1 through 4.

Use of the latch pipette was found to increase static, mean, and peak muscle activity of the EPB and APB muscles as well as the static and mean activity of the APL (Table 2), whereas the FPL muscle activity was reduced when the latch pipette was used. Figure 5 shows the mean APDF 10%, 50%, and 90% muscle activity level for each of the four muscles when using the latch pipette in comparison with the nonlatched pipette (Tasks 5 and 6 vs. Tasks 1 and 2).

Volume adjustment produced the greatest levels of muscle activity, as compared with all other tasks. Tip ejection also elicited high levels

TABLE 2: Changes in Muscle Activity or Plunger Force by APDF Level

	EPB			APL			FPL			APB			Force			
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	50%	95%	MCT	DC
High viscosity														↑	↑	
High precision	↑	↑	↑	↑	↑		↑			↑				↓		↑
Latch pipette	↑	↑	↑	↑	↑			↓		↑	↑	↑	n.a.	n.a.	n.a.	n.a.

Note. Significant differences (indicated as ↑ or ↓; $p < .05$) as compared with a low-viscosity, low-precision task using a standard (no latch) pipette. The high-precision task is associated with an increase of some measures of muscle activity but decreased peak thumb force. High viscosity increased mean cycle time (MCT), whereas high precision increased duty cycle (DC).

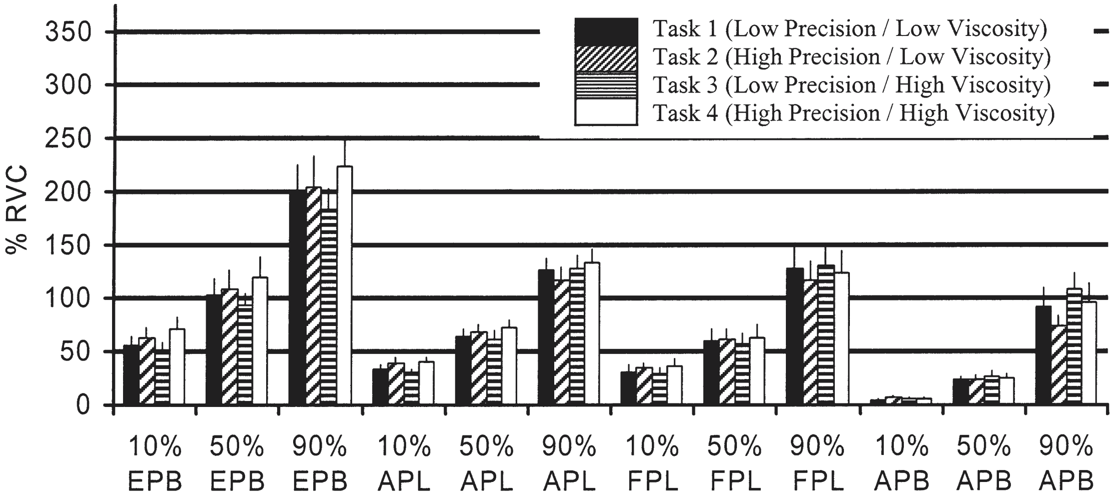

Figure 4. Mean EMG APDF levels (10%, 50%, and 90%) for the EPB, APL, FPL, and APB muscles for Tasks 1 through 4. Values are shown as a percentage of RVE ($N = 14$); error bars represent 1 *SEM.*

of muscle activity from the EPB, as compared with Tasks 1 through 6. Figure 6 shows the mean APDF 10%, 50%, and 90% muscle activity level for the three additional tasks commonly performed with pipettes.

DISCUSSION

This study found that pipetting task and pipette design can influence peak thumb force and activity of the muscles that move the thumb. Increased pipetting task precision leads to increased static muscle activity of all of the thumb movers tested (EPB, APL, FPL, and APB) and increased peak muscle activity of EPB. High-precision pipetting requires greater control of thumb motion, which is accompanied by increased static load of both the antagonists (EPB, APL) and agonists (FPL, APB). The antagonist muscles act to stabilize the metacarpal and carpometacarpal joints. The

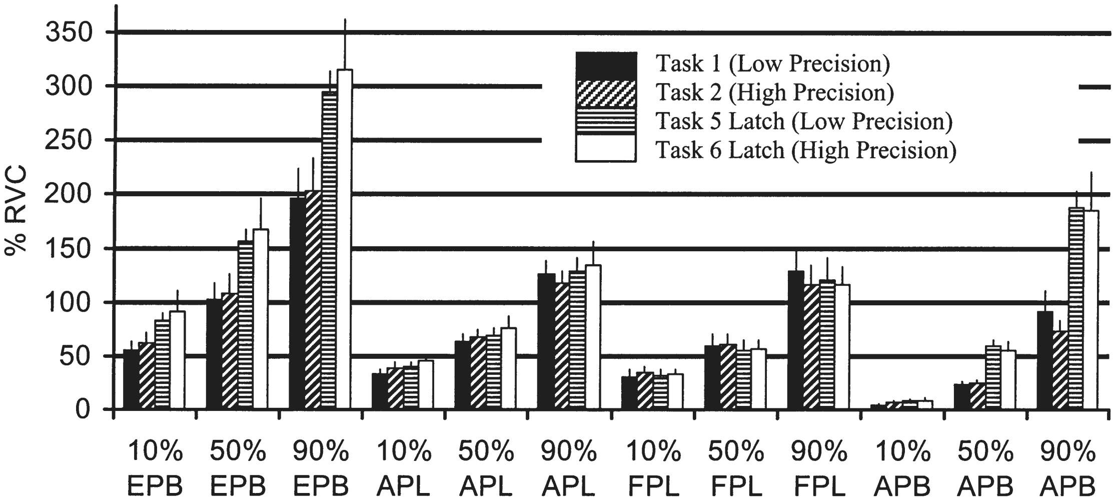

Figure 5. Mean EMG APDF levels (10%, 50%, and 90%) for the EPB, APL, FPL, and APB muscles while pipetting with and without a latch pipette. Tasks 1 and 2 were repeated using a latch pipette. Values are shown as a percentage of RVE ($N = 14$); error bars represent 1 *SEM.*

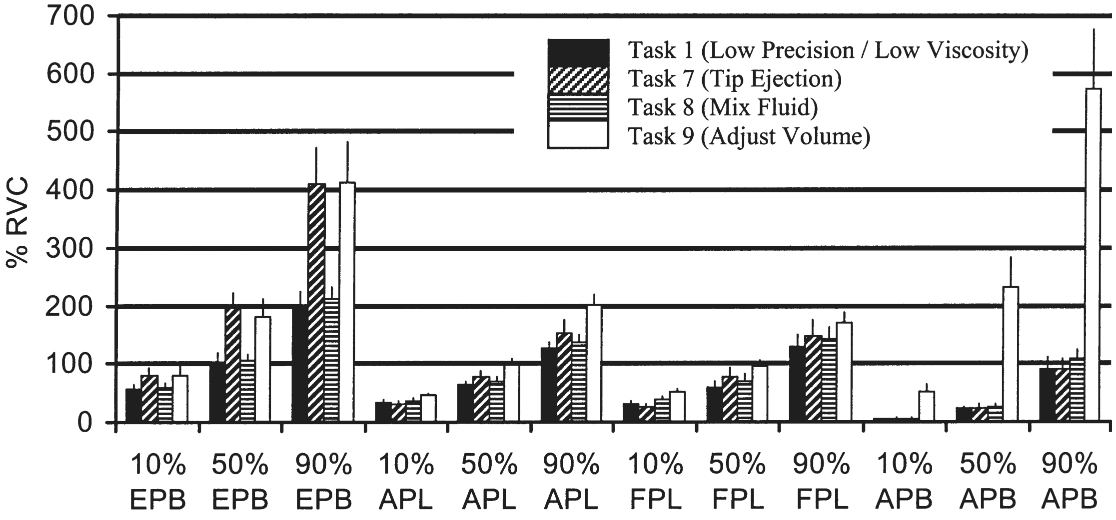

Figure 6. Mean EMG APDF levels (10%, 50%, and 90%) for the EPB, APL, FPL, and APB muscles for Tasks 1, 7, 8, and 9. Values are shown as a percentage of RVE (N = 14); error bars represent 1 *SEM.*

tendons to these muscles pass through the first extensor compartment at the wrist; therefore increased static activity of these muscles coupled with the metacarpophalangeal joint held in extension may increase the risk of developing tenosynovitis at this compartment site (e.g., de Quervain's disease; Moore, 1997). As a point of reference, the average static load (APDF 10%) of APL, as a percentage of MVC, increased from 10.6% to 13.3% MVC with high-precision tasks; this is an important increase, based on the endurance limits recommended by Bjorksten and Jonsson (1977). High fluid viscosity was found to have little effect on muscle activity but was associated with an increased peak force applied to the plunger, probably because of the increased resistance during fluid dispensing. It was also associated with an increase in mean cycle time.

Of the three additional tasks studied, volume adjustment produced the highest levels of muscle activity. This task involves turning a dial with the thumb and index finger. The small diameter of the dial, the limited contact friction between the dial and fingers, and the force required to turn the dial may explain the high levels of muscle activity during this task.

An unexpected finding was that the high-precision task was associated with a decreased peak force applied by the thumb to the plunger. This finding, which appears to contradict the EMG finding of no change in median or peak agonist muscle (APB, FPL) activity, may be attributable to users applying greater control while depressing the plunger and not applying as much force during blowout. This theory is supported by the observation of an increase in median muscle activity of the antagonists (EPB, APL) coupled with no change in the median activity of the agonists (APB, FPL). Median EPB activity or cocontraction increased from 9.6% to 11.2% MVC during performance of high-precision tasks, as compared with low-precision tasks. Finally, the increase in duty cycle, without a change in mean cycle time between tasks, means that the thumb moves slower under load during high-precision tasks, suggesting greater motor control. Another possible explanation for the decrease in load is viscous effects. Because the thumb moves slower during high-precision tasks, forces attributable to the viscous properties of the fluid would be reduced.

The goal of blowout is to dispense any residual fluid that may be in the tip of the pipette. Because blowout is a range of plunger displacement (beyond Point A in Figure 1), as opposed to a hard stop, users decide where to stop within this range. This leads to some interparticipant variability in thumb peak force. The observed values of peak force (APDF 95%), which always occur during blowout, reflect this. They fell between 23 and 35 N, nearly the entire range of the blowout region of the pipette.

The finding that peak force varied by task suggests that the task may influence where within the blowout displacement range users decide to stop. Peak forces were between 23% and 34% of maximum strength. These percentages are greater than those reported by Fredriksson (1995) because the pipette used in our study required a higher force to reach the blowout region (19 N, as compared with 14 N) and because our study measured actual force applied during a pipetting task, not estimated force.

A second unexpected finding was that the use of a latch pipette increased muscle activity of the EPB, APL, and APB. Because the number of plunger presses per cycle is reduced with the latch mechanism, thereby increasing rest time during the cycle and decreasing the duty cycle, it might be expected that muscle activity would decrease. In addition, the blowout spring is not present in the latch pipette, thus decreasing the force needed to dispense any residual liquid. There was a corresponding decrease in mean muscle activity of the FPL, but no similar decrease in peak FPL activity was observed.

A possible explanation for the increase in EPB, APL, and APB muscle activity may be found in the finger motions used with the latch pipette. After depressing the plunger, users suspended the thumb with the metacarpophalangeal joint in extension to keep it away from the pipette during the remaining steps (including latch manipulation), thereby leading to increased static muscle load. With a standard pipette, users tend to keep their thumb resting on the plunger and do not extend the thumb as far back. This may explain the increase in EPB and APL activity. The increase in APB muscle activity could be caused by the user having to abduct and flex the thumb during latch manipulation. This finding suggests that pipettes should be designed with surfaces or other features to allow and encourage the thumb to rest during some portion of the pipetting cycle and also to allow the thumb to generally be in a neutral posture rather than in extension or adduction.

A potential study limitation of the surface EMG data is cross talk. Because the muscles in the forearm are small and in close proximity to each other, it is difficult to isolate the activity of a single muscle using surface EMG. The EPB and APL may be the most difficult to isolate because they have overlapping fibers. However, the direction of action of both muscles is similar, so cross talk would not change the conclusions of this study. The tendons of both of these muscles are involved in de Quervain's disease. Therefore, an increase in load on either or both introduces a potential increase in risk.

Another limitation is that the thumb and wrist postures were not recorded. Wrist radial deviation and thumb extension may be risk factors for de Quervain's disease (Moore, 1997). The design of pipettes usually requires the thumb carpometacarpal joint to be in extension, but it is not known how often and to what extent the thumb assumes these postures.

Another limitation was that the accuracy of task performance was not measured. Participants were instructed to perform the tasks with the accuracy and speed that they would typically use at work. Whether or not participants actually collected the correct sample or pipetted the correct amount was not recorded. Several users exerted forces on the plunger that far exceeded the minimum required force to depress the plunger to the first stop. Others exerted forces close to the minimum required force. Because the participants were experienced pipette users, this interparticipant difference in force profile is probably part of the natural variation in how participants typically use pipettes. It may be possible to train users to change the applied force or modify the pipette so that applied peak forces are close to the minimum required.

A fourth limitation to the study is that the RVE values reported are missing a major lower frequency component of the EMG because of the high-frequency filter cutoff. This filtering, however, should minimally affect comparisons between conditions because all conditions received the same filtering.

Finally, comparisons were made for 16 different outcome measures, but no statistical correction for multiple comparisons was applied. An argument can be made that some of the outcome measures are independent, and therefore corrections for multiple comparisons are unnecessary. In addition, many more significant differences were found than would be attributable to chance alone.

CONCLUSIONS

Pipetting task and pipette design can influence the applied thumb force and the activity of the muscles that move the thumb. Tasks requiring high-precision pipetting (e.g., small volumes or careful tip placement) are associated with elevated static thumb muscle load and may pose a risk for tendon-related injuries or fatigue. It would be useful to verify these findings among employees performing real laboratory work. In order to reduce the risk of tendon disorders and forearm fatigue, interventions should be considered that would reduce risk factors. Proper training and modifying the pipette design may reduce thumb muscle activity and applied thumb force as well as decrease the duty cycle. Modifications to pipette design could include reducing or limiting forces during blowout, increasing the diameter of the volume adjustment dial or the required rotation force, modifying the plunger position to reduce awkward thumb postures, and adding surfaces upon which to rest the thumb.

REFERENCES

Bjorksten, M. G., Almby, B., & Jansson, E. S. (1994). Hand and shoulder ailments among laboratory technicians using modern plunger-operated pipettes. *Applied Ergonomics, 25,* 88–94.

Bjorksten, M. G., & Jonsson, B. (1977). Endurance limit of force in long term intermittent static contractions. *Scandinavian Journal of Work, Environment and Health, 3,* 23–27.

David, G., & Buckle, P. (1997). A questionnaire survey of the ergonomic problems associated with pipettes and their usage with specific reference to work-related upper limb disorders. *Applied Ergonomics, 28,* 257–262.

Delagi, E. F., Perotto, A., Iazzettim J., & Morrison, D. (1981). *Anatomic guide for the electromyographer* (2nd ed). Springfield, IL: Tomas.

Fredriksson, K. (1995). Laboratory work with automatic pipettes: A study on how pipetting affects the thumb. *Ergonomics, 38,* 1067–1073.

Jonsson, B. (1982). Measurement and evaluation of local muscular strain on the shoulder during constrained work. *Journal of Human Ergology, 11,* 73–88.

Milerad, E., & Ericson, M. O. (1994). Effects of precision and force demands, grip diameter, and arm support during manual work: An electromyographic study. *Ergonomics, 37,* 255–264.

Moore, J. S. (1997). De Quervain's tenosynovitis: Stenosing tenosynovitis of the first dorsal compartment. *Journal of Occupational and Environmental Medicine, 39,* 990–1002.

National Research Council and Institute of Medicine. (2001). *Musculoskeletal disorders and the workplace.* Washington, DC: National Academy.

Visser, B., Looze, M., Graaff, P., & van Dieen, J. (2004). Effects of precision demands and mental pressure on muscle activation and hand forces in computer mouse tasks. *Ergonomics, 47,* 202–217.

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