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# An investigation of hand forces and postures for using selected mechanical pipettes

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**Abstract**

The present study evaluated thumb, hand forces, wrist, forearm and shoulder postures used for pipetting with three selected mechanical pipettes. Twelve pipette users in a large university health system participated in pipetting simulation in their own laboratories to investigate the effects of pipette type, body posture (standing/seated), sample volume (200/1000 μL) and pipetting task on the physical risk factors. The thumb and hand forces were measured with 19 Flexiforce™ sensors. Wrist and forearm postures were measured with an electrogoniometer and a torsiometer, respectively. Humeral elevation as shoulder postural stress was assessed by observations from videos recorded during pipetting simulation. The study results showed several advantages of using the non-axial pipette over the traditional axial ones. The non-axial pipette was associated with approximately 2–6 times less thumb and hand force than the traditional axial pipettes. In addition, there were approximately 20–30% reductions in ulnar deviation and 30–70% reductions in humeral elevation to operate the non-axial pipette for most of the pipetting actions. One disadvantage of using the non-axial pipette appears to be increased forearm pronation by approximately 100–150% for the entire pipetting cycle, as compared to the axial pipettes. The results of the study may provide useful information regarding design of pipettes for reducing physical risk factors associated with pipetting.

**Relevance to industry**

This paper demonstrated hand forces and postures for common pipetting tasks with selected mechanical pipettes. The hand force and postural data for using axial and non-axial pipettes may provide key information for hand injury prevention due to pipetting in the industry.
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*Keywords:* Pipette; Non-axial design; Musculoskeletal disorders

## 1. Introduction

Pipetting is a very common task among laboratory workers. A variety of manual, plunger-operated mechanical pipettes have been widely used in laboratories. Typically the plunger, connected to the top of the barrel of a pipette, is depressed and released by the user's thumb through a spring-loaded mechanism to aspirate liquid. The pipette usually has a second thumb-operated trigger used to eject its disposable tip. The volume of the liquid to be dispensed can be adjusted by manually rotating the plunger or by depressing operating buttons, depending on the pipette's design. Most mechanical pipettes used in laboratories are single-channel and elongated/axial in shape.

During pipetting, users often engage in awkward postures. Axial pipettes typically require users to elevate their hands and elbows to obtain approximately 20–25 cm of work surface clearance. Fredriksson (1995) found from a video analyses that a typical pipetting posture involved 30° neck flexion, 20° shoulder abduction, 90° elbow flexion with the lower arm supinated at approximately 30°, and the

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wrist extended at 30°. Pipetting requires accurate and precise hand/arm positioning to transfer exact quantities of liquid from one vessel to another, causing users to maintain static postures. The weight of the pipette directly affects muscular strain in the shoulder, arm and wrist, caused by holding the pipette in static postures (Lintula and Nevala, 2006). In addition, repetitive thumb exertion caused by using the pipette plunger and tip ejection trigger may result in muscular strain to the hand (Wood et al., 1997).

Hand and thumb forces required by pipette design may cause strain to the hand and thumb. Wood et al. (1997) evaluated three pipettes on user comfort, fatigue, and satisfaction. The pipette that produced significantly less discomfort in the hand and wrist was the one that required significantly less hand force to operate (Wood et al., 1997). Hand force for pipetting can also be affected by wrist posture. Delp et al. (1996) reported that the maximal isometric moments generated by the radial/ulnar deviation decrease as the wrist deviates away from the neutral position. This study finding indicates the hand muscles of pipette users may be prone to being fatigued while pipetting in non-neutral position due to decreased hand forces that can be exerted for pipetting.

Many musculoskeletal disorders (MSD)-related physical risk factors for pipetting have been found in the literature. The relationship between pipetting and MSD development, however, remains largely unknown. The literature, however, does suggest that prolonged pipetting may increase the risk for MSDs (Bjorksten et al., 1994; Fredriksson, 1995; David and Buckle, 1997). One case study showed that there appears to be a relationship between manual pipetting and non-specific upper limb symptoms (Baker and Cooper, 1996). Bjorksten et al. (1994) found that if pipetting was performed for more than 300 h/year, the prevalence of hand and shoulder pain among laboratory workers increased, compared to the general Swedish working population. David and Buckle (1997) found that the reported occurrence of elbow and hand complaints was significantly higher in pipette users than non-pipette users. In addition, they also found that there was an increase in the percentage of the complaints as the duration of the working period involving continuous use of pipettes increased (David and Buckle, 1997). Results from a Scandinavian study showed that the MSD-related symptoms increased with increasing amount of time spent pipetting (Fredriksson, 1995).

To reduce the MSD physical risk factors related to manual pipetting, pipette design is of great importance (Fredriksson, 1995; Lee and Jiang, 1999; Asundi et al., 2006; Lintula and Nevala, 2006). It can influence applied thumb force and muscle activity (Asundi et al., 2006; Lintula and Nevala, 2006), performance of pipette users (Lee and Jiang, 1999), perceived muscular strain and usability (Lintula and Nevala, 2006). To our knowledge, the pipettes evaluated in the literature appear to be axial in design. Non-axial pipettes have not been assessed for the effects of their unique design on hand forces and postures used for various pipetting tasks. Therefore, the objective of this study was to investigate the hand forces and postures for pipetting using axial and non-axial pipettes.

## 2. Method

### 2.1. Subjects

Twelve laboratory technicians (11 women, 1 man) from two clinical laboratories in the university health system with an average of 16 years of experience in pipetting participated in the study. Subjects were all right handed without history of hand injury. The male subject was 180 cm in height and 93.2 kg in weight. The means and standard deviations of the female subjects' height and weight were $165.7 \pm 6.3$ cm and $70.4 \pm 17.2$ kg, respectively. All the subjects were familiar with various pipetting procedures required for their jobs. Prior to the pipetting simulation, they were instructed by the investigators about the procedure for performing different pipetting tasks for each simulation trial. They were also informed of risks of performing the pipetting simulation. The protocol for the pipetting simulation was reviewed and approved by the National Institute for Occupational Safety and Health (NIOSH) and the university health system's human subjects review boards.

### 2.2. Pipettes evaluated

Two popular traditional axial pipettes were selected for comparisons with the non-axial pipette. Fig. 1 presents the two axial (model A, Oxford Benchmate II, Mansfield, MA; model B, Eppendorf AG, Hamburg, Germany) and the non-axial pipette (model C, Ovation BioNatural, VistaLab, Mt. Kisco, NY). These pipettes covered the pipetting volume range of 200–1000 μL. The three tested pipettes were brand new. The three models had the same operational volumes from 200–1000 μL. Model A had an eject button in addition to the plunger, while model B had one

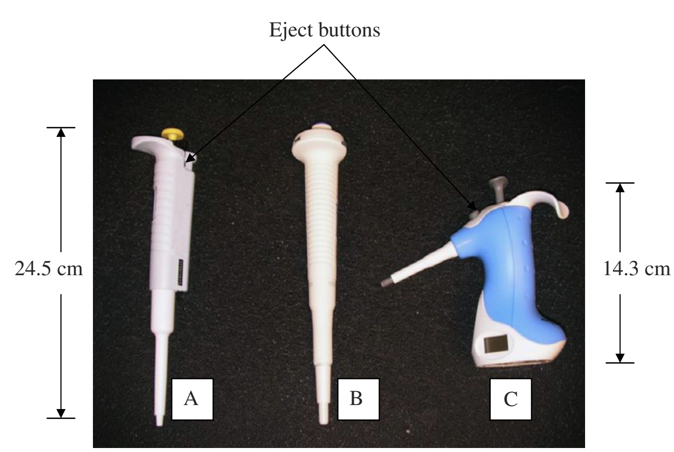


Fig. 1. Pipettes evaluated (2 traditional axial pipettes labeled A and B; 1 non-axial pipette labeled C).

plunger that was used for both aspirating sample and ejecting tip. Model C has a contour surface for holding the pipette body. The barrel of model C was not in line with the pipette body, requiring users to operate with the hand slightly pronated. Designed similar to model A, model C also had an eject button in addition to the plunger. With the aspiration volume set at 200 μL, the lengths of the pipettes without tip for models A, B and C were 24.5, 24.1 and 14.3 cm, respectively. The weights of pipette models A, B and C were 113, 98 and 156 g, respectively. The diameters of the pipette body or handle for models A and B were 2.47 and 2.48 cm, respectively. The average diameter (average of width and depth) of pipette C's body was 4.16 cm.

### 2.3. Measurements

#### 2.3.1. Hand force and thumb force

Hand and thumb forces used for pipetting were measured at a sampling rate of 100 Hz using the hand force measurement glove system. The system, shown in Fig. 2, consisted of a leather glove outfitted with 19 thin profile sensors (FlexiForce Sensors (FFS) Model A101-25, Tekscan Inc., South Boston, MA) that measured the interface pressure between a person's palm/fingers and the contact surface of the pipettes. Three sizes of the FFS glove (small, medium, large) were available for the subjects to choose from in order to fit their right hand. All wires connected to the sensors were taped to the back of the glove so that there were no interferences with pipetting. One investigator operated the custom software program, written with Labview 6.1 (National Instruments, Austin, Texas) on a portable computer and verbally guided the subjects to simulate each pipetting task. The other investigator videotaped the sagittal view of the arm and shoulder postures for the entire simulated pipetting cycle for observational postural analysis. The custom program calculated the time-series total hand force, which is defined as the sum of the force data from all 19 force sensors. In addition, the thumb force, defined as the sum of the force data from the two sensors on the first two thumb phalanges, was also calculated. Prior to the pipetting simulation, each of the FFS was individually calibrated using the method described by Kong and Lowe (2005). This involves a procedure in which the sensor is placed between the thumb and a platform mounted on a button style load cell. The investigator applies a ramp increasing thumb force over the range of forces from 0 to approximately 7 kg. The voltage output of the sensor is linearly regressed against the applied load as measured on the load cell. Coefficients of determination ($r^2$) exceeded 0.98 for all sensors. In the calibration procedure the sensor is covered completely by the thumb tip, which distributes the force over the entire sensor surface. Measurements of hand contact on grasped objects in measurement trials may result in situations where individual forces are distributed with incomplete coverage of the sensor and the force measured on the sensor is under-measured.

Fig. 2. FlexiForce™ sensors outfitted on a glove used for measuring hand force.

#### 2.3.2. Wrist and forearm posture

In the present study, the conventions for the measurements of wrist and forearm postures followed the conventions used by American Academy of Orthopaedic Surgeons (1965). The neutral point (0°) for the wrist and forearm marked the vertical position of the hand in parallel to the forearm. Palm down and up were pronation and supination, respectively. Flexion was towards the palm and extension was towards the back of the hand. Radial deviation was towards the thumb and ulnar deviation was towards the little finger. Wrist flexion/extension and radial/ulnar deviation postures were measured using a twin axis electrogoniometer (model XM65 Biometrics Ltd., Cwmfelinfach, England) and a torsiometer (model Q150, Biometrics Ltd., Cwmfelinfach, England). Each electrogoniometer and torsiometer consisted of two endblocks connected by a composite wire that had a series of strain gauges mounted around the circumference. As the angle between the two endblocks changed, the change in strain along the length of the wire was measured and equated to angle. The only difference between the electrogoniometer and the torsiometer was that the torsiometer only recorded forearm pronation/supination, whereas the electrogoniometer recorded wrist flexion/extension and radial/ulnar deviation. One endblock of the electrogoniometer was attached on the center of the subjects' carpals in line with the third metacarpal and the other was attached on the midline dorsal side of distal radius and ulna. One endblock of the torsiometer was attached at distal part of the ulna and the other was attached at tuberosity of the radius. Each electrogoniometer and torsiometer signal was sampled at 100 Hz and digitally low-pass filtered (6th order Butterworth) with a 10 Hz cut-off frequency.

A study showed that measurements for wrist flexion/extension and deviation are affected by cross-talk with forearm rotation (Spielholz, 1998). A custom made fixture that can rotate wrist and forearm at desired degrees in three axes was used to calibrate the electrogoniometer in three respective axes. This calibration procedure was performed by a multiple regression approach in which readings from the goniometer and torsiometer were used as regression variables (Lowe, 2004). Static recordings from the electrogoniometers were made in 27 fixture positions—3 combinations of radial/ulnar deviation, flexion/extension, and supination/pronation. The fixture-set angular positions were entered as dependent variables in the regression models and the electrogoniometer readings were entered as independent variables. First order terms, second order terms, and all interactions were included in a multiple regression model predicting the fixture-set angular position. The mean coefficients and standard deviations of determinations ($R^2$) predicting fixture-set angular position were $0.97 \pm 0.05$ for pronation/supination, $0.96 \pm 0.06$ for wrist flexion/extension and $0.87 \pm 0.07$ for radial/ulnar deviation. The $R^2$ values were equivalent to or exceeded those of some previous studies (Spielholz, 1998; Lowe, 2004). The calibrated goniometer/torsiometer readings were used for data analysis.

### 2.3.3. Shoulder posture

Ideally, direct measurements such as electrogoniometer measurements are preferred for measuring shoulder posture. However, due to a limited number of electrogoniometers available in the present study, an observational method was used for measuring shoulder posture. The Multimedia Video Task Analysis (MVTA) software program, developed at the University of Wisconsin, was used to determine the amount of time spent in different shoulder postures during pipetting simulation. The MVTA program helped automate time and motion analyses of visually discerned activities through a graphical user interface. Studies have shown desirable accuracies of the observational method with the MVTA program (Yen and Radwin, 2000; Spielholz et al., 2001). Yen and Radwin (2000) reported 7% error between the electrogoniometer and the observational method for shoulder posture.

One digital video camcorder (Sony Inc., model DCR-PC 120) set up for a sagittal/frontal view (refer to Fig. 3) was used for capturing shoulder postures during each pipetting simulation. Shoulder postures were recorded at a rate of 30 frames/s. Break points that defined the start and end of the change in shoulder posture were visually identified. Humeral elevation relative to the trunk was used as shoulder posture and was defined according to forward or lateral movements of the upper arm. If the upper arm moves away from neutral in the forward direction in the sagittal plane or lateral direction (adduction/abduction) in the frontal plane, or between the two planes, humeral elevation was identified. Humeral elevation greater than 45° was identified frame by frame in the video with the

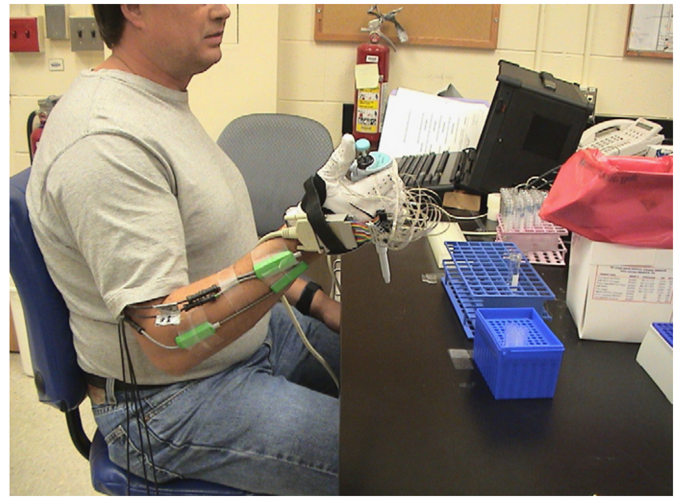

Fig. 3. Picture of a typical pipetting simulation setup.

MVTA program. Percentage of time for humeral elevation greater than 45° for each pipetting simulation trial was calculated by the MVTA program and used as a dependent variable to express shoulder posture as a physical risk factor.

## 2.4. Experimental design

A repeated measure analysis of variance (ANOVA) was used for four independent variables including three pipette types, two tasks, two sample volumes (200 and 1000 μL) and two body positions (standing, seated). Each subject underwent a total of 24 combinations (3 pipettes × 2 tasks × 2 volumes × 2 positions) of simulation trials that were randomized and blocked by body position.

## 2.5. Simulation tasks

A typical pipetting workstation (~91 cm in height) with sufficient leg room for sitting was set up in subjects' laboratories to simulate two common pipetting tasks that were actually performed by the subjects on a daily basis. The two pipetting tasks were standardized, meaning that the locations of the pipette, samples, tips and tip disposal basket were fixed on the workstation. Each pipette was positioned on the same location of the workstation to start with. Due to the design of pipette model C, it was in a "standing" position, upright on the workstation, whereas models A and B were positioned flat, lying down on the workstation. Task 1 was to complete an entire pipetting cycle with the right hand, while task 2 was to pipette with the right hand and hold a plastic vessel with the left fingers for aspirating sample. For both tasks, the subjects were instructed to overblow all the sample in the tip, then eject the tip into a disposal basket in front of them on the workstation. The sample volume for aspiration was set as either 200 or 1000 μL. For the standing position, the subjects stood upright in front of the workstation at their comfort. For the seated position, the subjects were able to adjust their sitting height via an adjustable chair, as they would normally be able to do at most actual pipetting workstations. A typical pipetting simulation setup is shown in Fig. 3.

### 2.6. Data processing and analysis

To evaluate the impact of the pipettes on different aspects of a pipetting cycle, a complete pipetting cycle was divided into five discrete actions including: (1) pick up pipette; (2) pick up tip; (3) aspirate sample; (4) overblow sample; and (5) eject tip. They are described as follows:

(1) *Pick up pipette*: the subjects picked up the pipettes with their right hand. Prior to each simulation trail, the pipettes were placed in the same position of the workstation, approximately 30 cm off the subjects' sagittal plane to the right.
(2) *Pick up tip*: the subjects picked up a tip with the pipettes. A box of tips, containing 12 × 8 pieces, was located 20 cm in front of the subjects and approximately 20 cm off the subjects' sagittal plane to the right on the workstation.
(3) *Aspirate sample*: aspiration involved depressing the plunger to a tactile stop and releasing the plunger until the desired amount of sample was reached and transferred into the tip. For task 1, the subjects aspirated sample (200 or 1000 μL) in a glass tube in a rack, located approximately 20 cm in front of them on the workstation; for task 2, they aspirated sample in the glass tube (200 or 1000 μL), which was held in their left fingers.
(4) *Overblow sample*: overblow sample required the subjects to depress the plunger completely to dispense and blow out sample. For both tasks, the subjects blew out sample into a glass vial in a rack, located approximately 20 cm in front of them and 20 cm off the subjects' sagittal plane to the left on the workstation.
(5) *Eject tip*: the subjects depressed the plunger (for model B) or the eject button (for models A and C) to eject the tip into a square disposal basket behind the rack of glass tubes, measuring 25 cm in height and approximately 35 cm in front of them on the workstation.

These actions were discerned by identifying the beginning and ending video frames of each action in the recorded video. Fig. 4 shows a typical time-series total hand force and postural data for a simulation trial. Mean values of the thumb and hand forces for each action of each simulation trial were calculated and used as dependent variables. Kumar (2001) reported that for postural stress, deviations from the neutral position to either side of the range of motion represent increasing hazard for MSD injury. Because dynamic pipetting actions performed by subjects typically exhibited posture in both directions from neutral, averaging the positive and negative readings for the posture profile of a given pipetting action might result

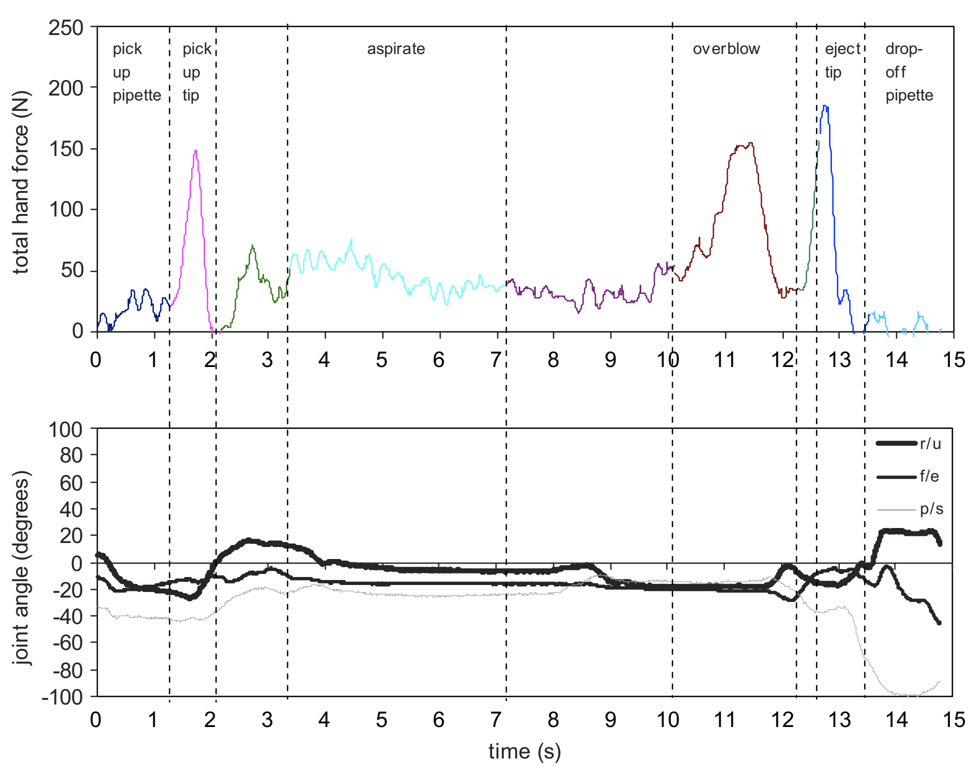


Fig. 4. A typical time-series total hand force and postural data for a simulation trial. Please note r/u: radial (+)/ulnar (–) deviation; f/e: flexion (+)/extension (–); p/s: forearm supination (+) /pronation (–). The dotted lines separate 5 pipetting actions.

in an average posture of zero or close to zero. Therefore, for each simulation trial, the time-weighted average angular displacement from neutral was calculated in both directions for radial/ulnar deviation, wrist flexion/extension and forearm pronation/supination. The more extreme of the two average angular displacements in both directions was used as the dependent variable in the statistical model.

The FFS, electrogoniometer/torsiometer and video data were collected in synchronization for each simulation trial to determine subjects' synchronized thumb, hand forces, wrist, forearm and shoulder postures for each pipetting action. Synchronization between the video recording and instrumentation measurements was accomplished by capturing an illuminated signal in the video recording corresponding to the instant that the computer acquisition of these measurements was initiated. The video frame showing the first appearance of the illumination was indexed to the first sample of the signals from the instrumentation acquired by the computer.

Personal Statistical Analysis Software (SAS) version 8.0 (SAS Institute Inc., Cary, NC) was used to perform a repeated measures ANOVA to determine the effects of pipette type, pipetting task, sample volume and body position on the thumb, hand forces, wrist, forearm and shoulder postures. PROC MIXED models were used for the ANOVA and Duncan multiple range test ($p<0.05$) was used for post hoc comparisons. The ANOVA was performed for each discrete pipetting action at a time. Least-square means calculated from the PROC MIXED models were used in the study findings.

## 3. Results

Table 1 summarizes ANOVA results for the significant effects of pipette type, pipetting task and body position on the thumb forces, hand forces, and wrist, forearm and shoulder postures. Pipette type and body position were found to be significant on most of the postural variables for most of the pipetting actions. Body position (seated vs. standing), however, was found to have no significant effect on any force measurements. In other words, the thumb and hand forces were only significantly associated with pipette type. Pipetting task was found to be significant on the wrist flexion/extension for overblow sample as well as the humeral elevation greater than 45° for aspirate sample. Sample volume was found to have no significant effect on any dependent variables.

### 3.1. Thumb force

Fig. 5 shows the means of the thumb force used for operating the three pipettes for the five pipetting actions. Compared to models A and B, approximately 30–45% reduction ($p<0.05$) in the thumb forces for operating model C for pick up tip, aspirate sample and overblow sample was found. Pick up pipette did not require operating the plunger or eject button. Therefore, no significant difference in the thumb force for pick up pipette between the three pipettes was found. The thumb force for operating model B for eject tip was found to be 3 times and 4 times greater ($p<0.05$) than that for models A and C, respectively, while there was no significant difference in such thumb force between models A and C.

### 3.2. Hand force

Fig. 6 shows the means of the hand force used for operating the three pipettes for the five pipetting actions. There was a significant decrease in the hand force for using model C for every pipetting action, as compared to models A and B. The means of the hand force for using model C for the 5 pipetting actions in sequence were 17.25, 26.46, 30.28, 34.50 and 23.52 N, respectively. Generally, the amount of total hand force associated with models A and B was 2–6 times greater than that for model C.

### 3.3. Wrist deviation

The results from the goniometer measurements showed that a range of 12–22° ulnar deviation was used for all five pipetting actions. Fig. 7 shows the means of the ulnar deviation used for operating the three pipettes for the pipetting actions. Ulnar deviation used for model C for pick up pipette, pick up tip and aspirate sample, were approximately 25% less than that for models A and B ($p<0.05$) , while there was no significant difference between models A and B for the three pipetting actions. No significant difference in mean ulnar deviation for overblow sample was found among the three pipettes. The values of mean ulnar deviation for eject tip with models A

Table 1
List of the significant effects ($p<0.05$) of pipette type (P), pipetting task (T) and body position (B) on the thumb, hand forces, wrist, forearm and shoulder postures

| | Pick up pipette | Pick up tip | Aspirate | Overblow | Eject tip |
|---|---|---|---|---|---|
| Thumb force | P | P | P | P | P |
| Hand force | P | P | P | P | P |
| Ulnar deviation | P, B | P | P, B | None | P, B |
| Wrist extension | P, B | P, B | P, B | T | P, B |
| Forearm pronation/supination | P | P, B | P | P | P |
| Humeral elevation | B | P, B | P, B,T | P | P, B |

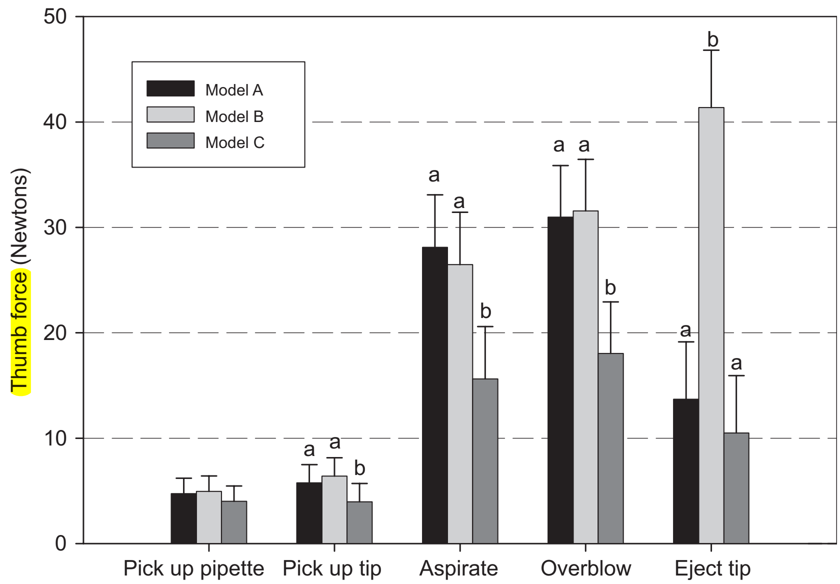


Fig. 5. Means and standard errors of the thumb force used for operating three different pipettes for 5 pipetting actions ($N = 12$; a and b: significantly different level at $p<0.05$).

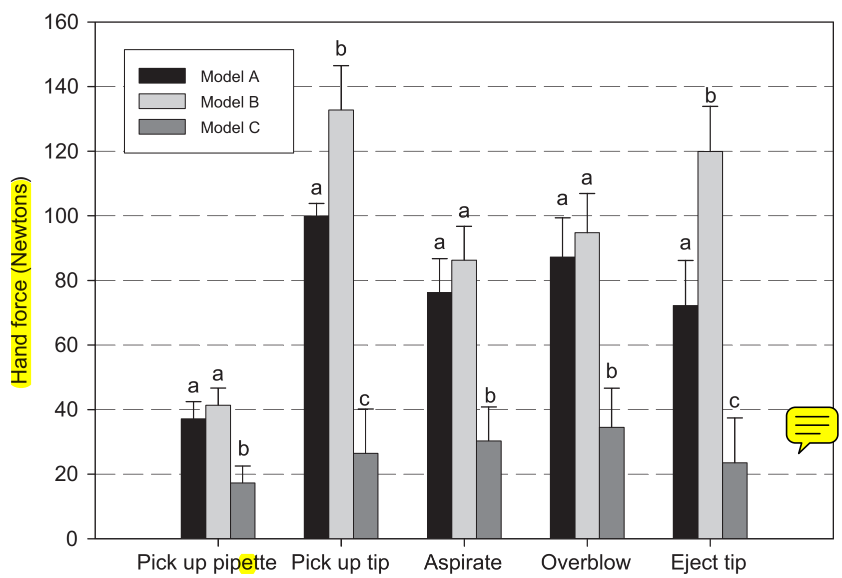


Fig. 6. Means and standard errors of the hand force used for operating three different pipettes for 5 pipetting actions ($N = 12$; a, b and c: significantly different level at $p<0.05$).

and B were found to be significantly smaller than that for model C.

### 3.4. Wrist extension

A range of 23–41° wrist extension was found to be used for the three pipettes throughout the entire pipetting cycle. Fig. 8 shows the means of the wrist extension used for the three pipettes for the five pipetting actions. There was no significant difference in mean wrist extension between the three models for pick up pipette, pick up tip and overblow. Compared to models A and B, approximately 25% reduction ($p<0.05$) in the mean wrist extension for aspirate sample with model C was found. The mean wrist extension for eject tip with model B was approximately 10° greater ($p<0.05$) than those for models A and C, while there was no significant difference between models A and C.

### 3.5. Forearm pronation/supination

Fig. 9 shows the means of the forearm pronation/supination used for operating the three pipettes for the five pipetting actions. For models A and B, a range of approximately 20–40° forearm pronation was used for all the pipetting actions, except for aspirate sample. Due to the non-axial design of model C, the subjects were forced to

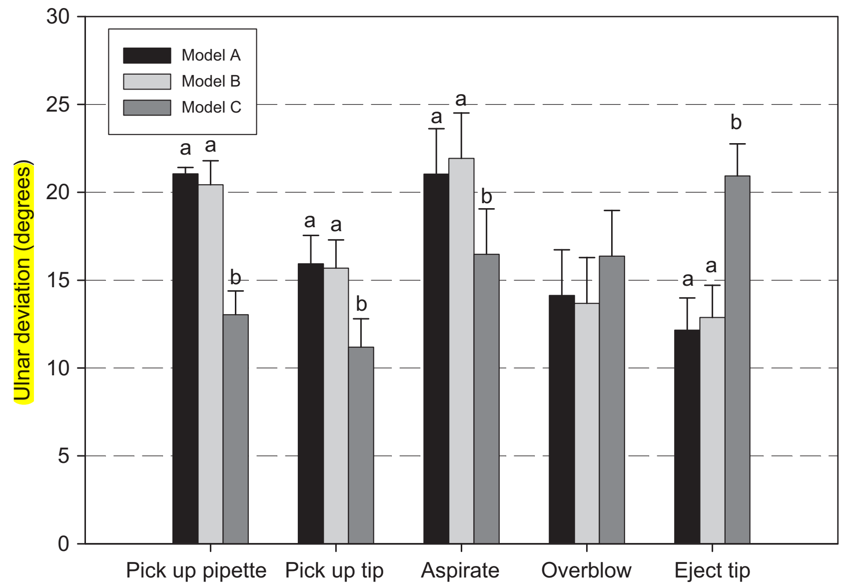


Fig. 7. Means and standard errors of the ulnar deviation used for operating three different pipettes for 5 pipetting actions ($N = 12$; a and b: significantly different level at $p<0.05$).

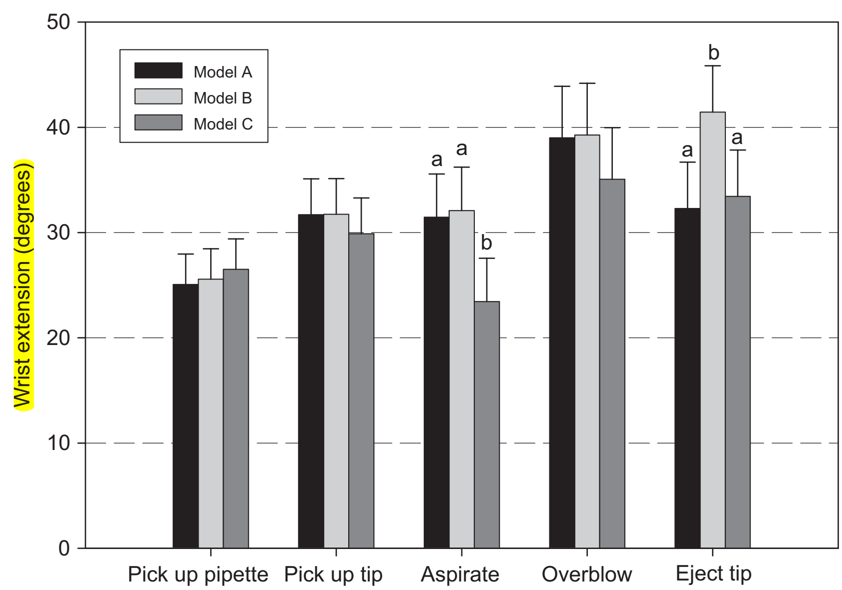


Fig. 8. Means and standard errors of the wrist extension used for operating three different pipettes for 5 pipetting actions ($N = 12$; a and b: significantly different level at $p<0.05$).

operate it in pronation through the entire pipetting cycle. For most pipetting actions, the forearm pronation used for model C was found to be approximately 2.5 times greater than that for models A and B. There was no significant difference in forearm pronation or supination for using models A and B for every pipetting action.

### 3.6. Humeral elevation

Table 2 presents the means of percentage of time with humeral elevation greater than 45° used for operating the three pipettes for the five pipetting actions. The means of percentage of time with humeral elevation greater than 45° for model C for most pipetting actions were significantly smaller ($P<0.05$) than for models A or B. For pick up tip, model C showed a significant decrease in humeral elevation with 13.1% of time with humeral elevation greater than 45°, as compared to 39.2% and 36.5% for models A and B, respectively. As the subjects operated the pipettes through the five pipetting actions, humeral elevation greater than 45° appeared to increase. The percentage of time with humeral elevation greater than 45° for all three pipettes were all greater than 68.9% for overblow and 84.5% for eject tip.

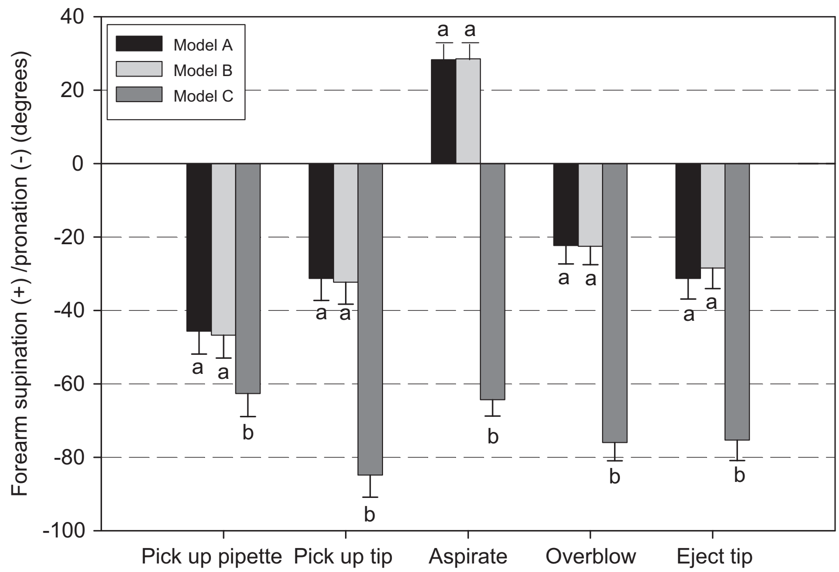


Fig. 9. Means and standard errors of the forearm pronation/supination used for operating three different pipettes for 5 pipetting actions ($N = 12$; a and b: significantly different level at $p<0.05$).

Table 2
Means (standard errors) of percentage of time with humeral elevation greater than 45° used for the three different pipettes for 5 pipetting actions

| Pipette model | Pick up pipette | Pick up tip | Aspirate | Overblow | Eject tip |
|---|---|---|---|---|---|
| A | 10.0 (3.7) | 39.2 (8.1)[a] | 52.3 (9.4)[a] | 73.0 (8.8)[a] | 87.1 (6.6)[a] |
| B | 10.7 (3.7) | 36.5 (8.1)[a] | 52.5 (9.4) | 80.5 (8.8)[a] | 89.6 (6.6)[a] |
| C | 6.1 (3.7) | 13.1 (8.1)[b] | 36.6 (9.4)[b] | 68.9 (8.8)[b] | 84.5 (6.6)[b] |

$N = 12$; a and b: significantly different levels at $p<0.05$.

Table 3
Means (standard deviations) of percentage of simulation task completion time for each pipetting action by pipette model

| Pipette model | Pick up pipette | Pick up tip | Aspirate | Overblow | Eject tip |
|---|---|---|---|---|---|
| A | 20.8 (6.6) | 13.2 (4.3) | 31.2 (6.1) | 19.6 (4.8) | 14.9 (7.6) |
| B | 21.5 (8.1) | 12.0 (3.6) | 33.1 (7.6) | 17.4 (4.2) | 16.0 (4.8) |
| C | 17.6 (8.3) | 15.9 (6.5) | 34.5 (6.6) | 20.4 (4.8) | 11.6 (3.5) |

Total time from pick up pipette to completion of eject tip is 100%; each trial was considered an independent trial, $n = 96$.

### *3.7. Percentage of simulation task completion time for each action*

Table 3 presents the mean percentage of simulation task completion time of the three pipette models for the five pipetting actions. The means and standard deviations of the total time in seconds for completing one cycle of a simulated pipetting task for models A, B and C were $9.8 \pm 2.7$, $9.1 \pm 2.6$ and $8.8 \pm 2.2$, respectively. For all three models, it took the subjects approximately an average of 0.2 s longer to complete task 1, as compared to task 2. Due to the short time duration (<1–2 s) for each pipetting action, the authors chose to not perform a qualitative statistical analysis for the percentage of time for each pipetting action. The effects of pipette type, body position, pipetting volume on completion time for the entire pipetting task, however, were analyzed for their statistical differences. Pipette type, body position and pipetting volume did not significantly affect the time in completing one pipetting cycle. The patterns of the mean percent of time of the three pipettes for the pipetting actions were similar with more than 30% of time spent on aspirate sample.

## 4. Discussion

As shown in Fig. 5, the thumb force required to operate models A and B was very similar within each task, except for eject tip. The thumb force to operate model B for eject tip was found to be 3–4 times greater ($p<0.05$) than that for models A and C. Models A and B had a similarity in design and operation, except for eject tip. Model B had one plunger to aspirate sample and eject tip, while model A had a separate button by the plunger to eject tip. The difference in the force measurements may be explained by the fact that there was only one spring loading mechanism in model B in one plunger/eject button design, whereas there were two spring mechanisms in model A—one for the plunger and one for the eject button. The separate eject button for model A might have been designed so that lower levels of the thumb force were required to operate. Model B required the subjects to depress the plunger completely to eject a tip and therefore greater levels of thumb force were needed for operating such action.

The thumb forces exerted by the subjects for operating model C seemed to be greater than manufacturer-reported forces. The manufacturer's reported plunger forces for operating model C for the aspirate, overblow and eject tip actions were 8.62, 10.78 and 3.92 N, respectively. The thumb forces measured in this study for the three pipetting actions were 15.58, 18.03 and 10.49 N, respectively. There are two explanations for the discrepancy between the manufacturer's reported thumb forces and those measured in the present study. The first, and less likely, of these explanations is measurement error with the sensors. Our work with these sensors in previous studies has revealed that when measurement errors occur they are typically in the direction of force *under-measurement* due to incomplete coverage of the sensor between the hand region and the grasped object. In calibration the sensor is completely covered by the thumb tip during loading to known force levels. In task measurements sensors can make partial contact with the grasped object, depending on the configuration of the hand and the object grasped. This partial contact distributes less than the full contact pressure over the sensor, so that the calibration equation predicts less than the true contact force. Thus, it is unlikely that a measurement error in the present study would result in an *over-measurement* of the contact force at the thumb. The more likely explanation for the discrepancy between the manufacturer's reported values and those found in the present study is that the manufacturer reports the idealized case of the minimum required force to actuate the plunger trigger. It is expected that this minimum required force would be exceeded in a pipetting task where the worker modulates the trigger force. Differences between the minimum required grip/contact force and the actual grip/contact force exerted in functional tasks have been described in other work (Westling and Johansson, 1984; Cole, 1991).

Most pipette studies (Fredriksson, 1995; Lee and Jiang, 1999; Asundi et al., 2006) in the literature focused on thumb force, hand muscle activity and wrist posture for specific pipetting actions—aspirate, overblow or eject tip. In these studies, force, muscular activity and postural measurements were made for a specific paused pipetting moment or a static posture for aspirate, overblow or eject tip. With the measurement system used in the present study, the subjects performed more realistic pipetting trials, in an uninterrupted continuous manner, without being asked to stop for measurements. In a study by Lintula and Nevala (2006), where the muscle activity, wrist posture and usability for three axial pipettes were investigated, the ulnar deviation (6–10°) for pipetting was smaller than that (16–22°) found in the present study. The discrepancy is likely caused by the fact that the pipetting tasks in Lintula's study were not standardized and adjusted according to subjects' preference, while the pipetting tasks investigated in the present study were standardized across all subjects. Despite the difference in study methods, the majority findings about the force and posture measurements in the present study appear to be comparable to those reported in previous literature. For example, the thumb force measured (20–35 N) for overblow in Asundi's study (2006) is similar to that (18–32 N) in the present study. The wrist posture measured (20–27° extension) for aspirate in Lintula's study (2006) and that measured (30° extension) in Fredriksson's study (1995) are comparable to our findings (23–32° extension).

A range of 12–22° of ulnar deviation was found to be used by the subjects for the entire pipetting cycle for all three models. The ulnar deviation for model C for pick up pipette, pick up tip and aspirate sample was found to be about 5–8° less than that for models A and B. The ulnar deviation for model C for eject tip, however, was about 8° greater than that for models A and B. The greater amount of the ulnar deviation for model C for eject tip was caused by the fact that the disposal basket was placed in front of the subjects, where the right handed subjects were forced to deviate their right wrist towards the ulnar to eject tip. The excessive amount of wrist deviation ($>20°$) may be fixed by re-positioning the disposal basket to the right side of pipette users when using model C. Generally, increased ulnar deviation was required for using axial pipettes such as models A and B due to the greater clearances required for such models for pick up tip and aspirate sample, as compared to the non-axial design such as model C.

To our knowledge, this study was the first to evaluate hand grip force in pipetting. It was found that approximately 20–40% of the hand grip force was needed for operating the non-axial pipette for different pipetting actions, compared to the two selected axial pipettes. It should be noted that the exerted hand grip forces for pick up tip with the axial pipettes were found to be the highest among all pipetting actions. Kong and Lowe (2005) reported that maximum hand contact force decreased as the diameter of a cylindrically shaped handle increased in the range of 2.5–5.0 cm diameter handles. In that study the maximum total hand contact forces measured with 16 thin profile force sensors on the finger and palmar regions were found to be 662 and 390 N for 2.5 cm (handle size for pipettes A and B in the present study) and 4 cm (handle size for pipette C in the present study) handle diameters, respectively. Based on these hand force capabilities, the percentages of maximum exerted hand forces for the pick up tip action with pipette models A, B and C were 15%, 19% and 6.5%. This finding suggests that the lower percentage of the maximum exerted hand grip force used for pick up tip with model C is less likely to cause muscular fatigue. The advantages of model C can be enhanced by the fact that the ulnar deviation used for pick up tip with model C was 5° less than that for models A and B. Force exerted by the thumb and hand in ulnar deviation for repetitive pipetting presents a potential for cumulative hand trauma such as carpal tunnel syndrome and tenosynovitis (Armstrong et al., 1987). Therefore, reduction of thumb and hand force in ulnar deviation required for operation should be a major pipette design consideration for hand injury prevention.

A change in forearm rotation from pronation to supination for aspirate sample with the axial pipettes possibly resulted from the tasks requiring the subjects to aspirate sample in a small glass tube either in a rack or in their left hand. This postural change seemed to be very common using axial pipettes to obtain a proper visibility. For model C, due to its non-axial design, the subjects were forced to pronate their operating forearm for the entire pipetting cycle. Approximately as twice as much forearm pronation was required for operating model C, as compared to models A and B. A study showed that the lowest pressure in the carpal tunnel occurred at 45° forearm pronation and 45° metacarpophalangeal flexion, as compared to different levels of forearm supination/pronation (Rempel et al., 1998). It was suggested by Rempel et al. (1998) that a forearm rotation angle near 45° pronation and a metacarpophalangeal 45° flexion angle should be considered for the design of hand-intensive tasks. This notion appeared to be considered in the design of model C. Conversely, Terrell and Purswell (1976) found that the pronated forearm allowed only 87% of the grip strength of the supinated forearm due to the shortened flextor digitorum superficialis from supination to pronation. However, a decrease in grip strength when the forearm is in pronation, as required to operate model C is unlikely to result in a decrease in pipetting performance and hand cumulative trauma disorder due to the low hand grip forces required for operating model C.

The significantly decreased durations for humeral elevation greater than 45° for using model C resulted from its shorter dispensing barrel, as compared to models A and B. As the subjects operated the pipettes through the end of the pipetting cycle, there was a significantly decreasing gap in humeral elevation greater than 45° between the axial pipette (model A or B) and the non-axial pipette (model C). This trend was probably caused by the categorization of the observational postural analysis for humeral elevation. A gross category (neutral, 0–45°, >45°) was used for the postural analysis using the MVTA program. When the upper arm was elevated near the boundary between 2 categories, a misclassification of the postural analysis might have occurred. This is a limitation of observational-based postural analysis methods that has been described by Keryserling (1986) and Lowe (2004).

The ANOVA results of this study showed that body position, pipetting task and sample volume did not cause any significant difference in the thumb and hand forces required for pipetting. This finding suggests that the mechanics and architecture of a pipette determine the thumb and finger forces. According to the ANOVA results, body position was found to have several significant effects on wrist, forearm and shoulder postures. Pipetting in seated position resulted in smaller amounts of wrist extension and pronation, while pipetting in standing position resulted in smaller amounts of ulnar deviation and humeral elevation. This finding suggests that altering position during the day between sitting and standing while pipetting may reduce cumulative strain in the whole body, including the body joints measured in the present study.

The mean percentages of the pipetting simulation completion time for all pipetting actions were similar among the three models. The subjects spent more than 30% of the completion time on aspirate sample, while they spent somewhere between 12% and 22% of the completion time for each of the rest of the pipetting actions. Aspirate sample required precise hand–eye coordination and proper motor control for operating the plunger. Therefore, the percentage of time for aspirate sample was found to be greater than other pipetting actions. The mean total time required to complete a cycle of the simulated pipetting tasks with the models A, B and C were 9.8, 9.1 and 8.8 s. It appears that model C is somewhat more efficient than models A and B. A full-scaled evaluation of performance measures of the pipettes, such as volume set up time, accuracy and fault rate of the pipettes, is recommended to determine the efficacy of the pipettes.

## 5. Conclusions

The results of the study revealed that exerted thumb and hand forces for pipetting were dictated by pipette design, regardless of pipetting task, body position and sample volume. Pipetting in seated position resulted in decreased wrist extension and pronation, while pipetting in standing position resulted in decreased ulnar deviation and humeral elevation. The architecture and mechanics of the non-axial pipette enables users to significantly reduce hand force as well as wrist and shoulder postural stress due to pipetting. One disadvantage of using the non-axial pipette, however, appears to be increased forearm pronation throughout the entire pipetting cycle, as compared to the axial pipettes. Further experimentation with non-traditional pipette design may result in greater reductions in MSD risk factors associated with pipetting.

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**Disclaimer**

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