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Editor's comment: Highly repetitive manual tasks are implicated in the development of musculoskeletal disorders such as carpal tunnel syndrome and tendinitis, which are the cause of much pain and discomfort to manual operators, including clinical laboratory workers. By measuring the kinematics and tendon displacements in the thumb during pipetting, the present study aimed to determine if the stresses associated with manual pipetting are comparable to activities such as typing or nail gun operations. The finding that accumulated tendon displacement is a potential measure of musculoskeletal loading may afford the means to establish safe operating limits for those whose work involves performing such tasks on a daily basis.

Richard Black, Editor in Chief

The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement

John Z. Wu[a,*], Erik W. Sinsel[a], Justin F. Shroyer[a], Daniel E. Welcome[a], Kristin D. Zhao[b], Kai-Nan An[b], Frank L. Buczek[a]

[a] National Institute for Occupational Safety & Health, Morgantown, WV 26505, USA
[b] Biomechanics Laboratory, Division of Orthopedic Research, Mayo Clinic, Rochester, MN 55905, USA

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ABSTRACT

Strong evidence indicates that highly repetitive manual work is associated with the development of upper extremity musculoskeletal disorders (MSDs). One of the occupational activities that involves highly repetitive and forceful hand work is manual pipetting in chemical or biological laboratories. In the current study, we quantified tendon displacement as a parameter to assess the cumulative loading exposure of the musculoskeletal system in the thumb during pipetting. The maximal tendon displacement was found in the flexor pollicis longus (FPL) tendon. Assuming that subjects' pipetting rates were maintained constant during a period of 1 h, the average accumulated tendon displacement in the FPL reached 29 m, which is in the lower range of those observed in other occupational activities, such as typing and nail gun operations. Our results showed that tendon displacement data contain relatively small standard deviations, despite high variances in thumb kinematics, suggesting that the tendon displacements may be useful in evaluating the musculoskeletal loading profile.

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1. Introduction

Strong evidence indicates that highly repetitive manual work is associated with the development of upper extremity musculoskeletal disorders (MSDs) [1–3]. For example, Silverstein et al. [4] investigated the prevalence of carpal tunnel syndrome (CTS) among 652 active workers in 39 jobs from seven different industrial sites and found that high force combined with high repetitiveness had more than a multiplication effect in causing the development of CTS. The prevalence of CTS among workers in high force and more repetitive jobs was found to be more than nine times that among workers in low force and low repetitive jobs [4]. In a separate study, the risk of tendinitis in workers in highly repetitive forceful jobs was found to be 29 times greater than that in low force and less repetitive jobs [5]. One of the occupational activities that involves highly repetitive and forceful hand work is manual pipetting in chemical or biological laboratories.

Manual pipetting involves repetitive motion of the thumb for extracting and dispensing fluids, during which the muscles/tendons and articular joints of the thumb, hand and wrist are exposed to both highly repetitive motion and high loading. A survey-based study [6] showed that almost 90% of pipette users, who continuously used pipettes for more than an hour on a daily basis, reported hand and/or elbow disorders. Several researchers have quantified the force applied on the pipette and musculoskeletal loading during pipetting. Fredriksson [7] assessed the push forces at the thumb required to operate a pipette and compared them with the participants' thumb strength. She found that the peak push force in operating the pipette is 18.4% and 14.5% of the push force capacity for female and male subjects, respectively. More extensive biomechanical analysis

* Corresponding author at: NIOSH/CDC, 1095 Willowdale Road, MS-2027, Morgantown, WV 26505, USA. Tel.: +1 304 285 5832; fax: +1 304 285 6265.
E-mail address: jwu@cdc.gov (J.Z. Wu).

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Table 1
Subjects' anthropometry data. The hand length and breadth are defined as in literatures [22,23].

Subject #	1	2	3	4	5	6	7	8
Gender (F/M)	M	F	F	F	F	M	M	M
Age (years)	26	30	29	24	31	29	25	26
Body mass (kg)	94.5	59.2	76.1	58.2	97.5	100.6	91.1	136.4
Height (cm)	174.5	165.7	166.9	158.3	160.4	182.1	175.4	177.8
Hand breadth (cm)	9.6	8.6	8.1	8.6	8.7	9.1	9.8	10.0
Hand length (cm)	19.3	17.0	18.0	18.0	17.1	19.3	19.9	20.1

was performed by Asundi et al. [8], who evaluated the thumb push force and activities in four extrinsic muscles for different pipetting tasks. They found that high-precision tasks significantly increased static muscle activity but reduced peak thumb force on average 5% as compared with low-precision tasks; in addition, pipetting high-viscosity fluids increased peak thumb forces on average by 11% compared with pipetting low-viscosity fluids. The force magnitude and excursion of muscles/tendons of the thumb during pipetting were not evaluated in the previous studies.

One of the proposed mechanisms of tenosynovitis is friction between the tendons and their synovial sheaths [9]; friction is caused by sliding of the tendon in its sheath and the contact force between the tendon and the sheath. Moore et al. [10] evaluated correlations of different biomechanical measures to quantify the potential risk of cumulative trauma disorders in different occupational manual tasks and they found that the measure of the tendon/sheath frictional work and the tendon force are closely correlated with injury outcomes found in epidemiological studies [4]. Based on that injury mechanism, Sommerich et al. [11] proposed tendon travel (i.e., displacement) as one of the generic measures to evaluate the biomechanical profile of selected occupational hand-intensive tasks. The tendon displacement (or tendon excursion) has been utilized to quantitatively evaluate the biomechanical stress among different typing jobs [12]. For three representative typing jobs, Sommerich et al. [12] obtained average tendon displacement of 59 m/h, 38 m/h, and 30 m/h, respectively, for accounting clerk, service representative, and word processing workers. The average tendon displacement per shift for these jobs was from 86 m to 273 m. Nelson et al. [13] studied the effects of keyboard orientations on finger kinematics and tendon displacement and they found the latter to be sensitive to keyboard orientation. They used tendon displacement to evaluate the effects of pitch, roll, and yaw angles of the keyboard on the biomechanical stress of the hand. Lowe et al. [14] investigated the effects of various nail gun trigger mechanisms on musculoskeletal loading in the index finger; they found that the accumulated tendon displacements varied from 22 m to 60 m during a typical workday, depending on the type of guns, trigger mechanism, and nature of the nailing job. In these previous studies, either the flexor digitorum profundus (FDP) or the flexor digitorum superficials (FDS) was analyzed, since they are the two major finger flexor tendons that are involved in flexion of all four fingers. Ugbolue et al. [15] measured the tendon displacements at the wrist in response to finger movements using cadaveric specimens and found that the tendon displacements for the FDS and FDP are similar and closely correlated.

The purpose of this study is to evaluate the tendon displacements in the thumb during pipetting, and to compare our results with those observed during other occupational activities, such as typing and nail gun operations. Our hypothesis is that the biomechanical stress associated with tendon displacements during pipetting will be comparable with those observed in typing and nail gun operations. The tendon displacement is the accumulated tendon excursion during pipetting in the current study.

2. Methods

2.1. Experimental set-up and test protocol

The test-setup in the study is similar to that used in our previous study [16] (Fig. 1A). Briefly, a typical thumb-activated pipette (P300, Pipetman, Gilson, Inc., Middleton, WI, USA) was used. Eight subjects (four male and four female; age 27.5(2.6) years; body mass 89.2(25.3) kg; height 170.1(8.6) cm) participated in the study

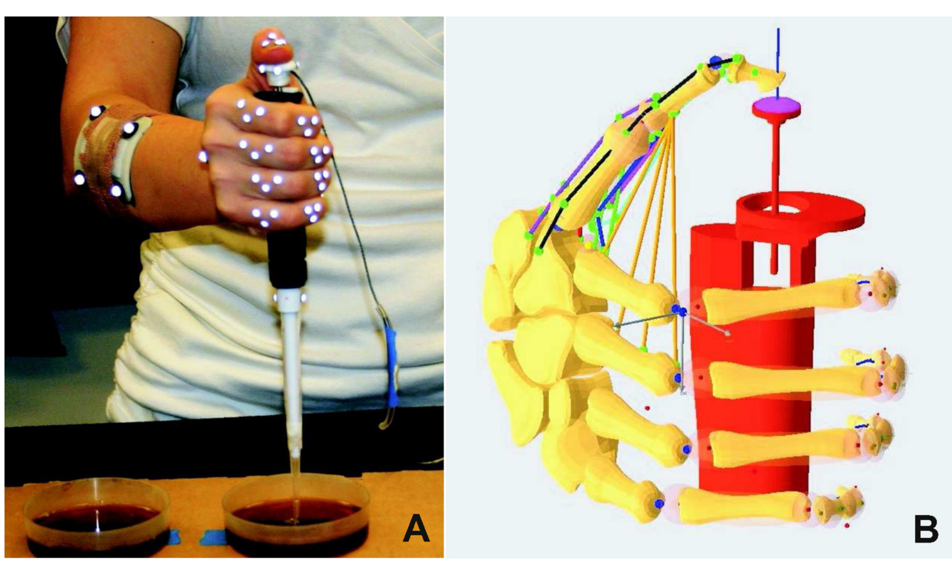

Fig. 1. Experimental set-up and modeling of pipetting. (A) A subject operating the pipette during the testing and (B) model of the entire hand with thumb, containing detailed muscle-tendon connections.

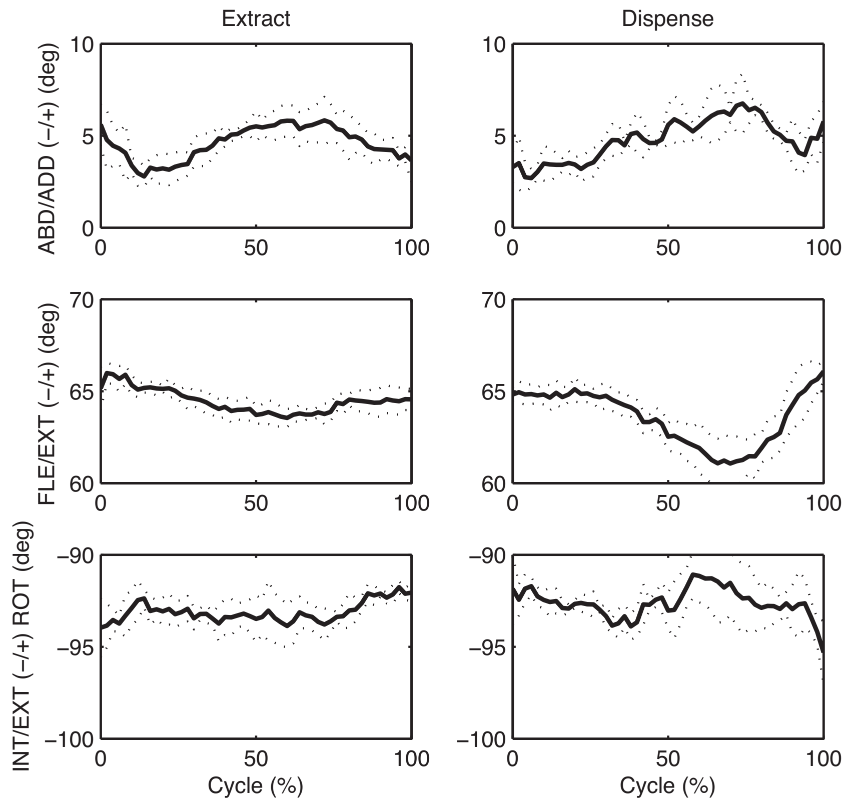

Fig. 2. Representative CMC joint angles as a function of work cycle. Left column: extraction cycle. Right column: dispensing cycle. Solid lines – mean; dotted lines – standard deviation.

following informed consent approved by the local human subjects committee. All subjects were right-handed laboratory technicians with a minimum of two years of experience using manual pipettes on a daily basis. Subject anthropometry data are listed in Table 1. Subjects were instructed to extract the fluid from one container on their left side and dispense it to another container on the right side. The containers were placed 120 mm apart center-to-center, which was typical in the work environment. The subjects were instructed to pipette at a pace consistent with their routine use of pipettes, and to repeat the same procedure in the pipetting task throughout a 60 s session. No particular pipetting rate was set for the subjects. Before data collection, subjects were afforded the opportunity to practice and become comfortable with the setup for about 2 min. To ensure greater consistency for each pipetting

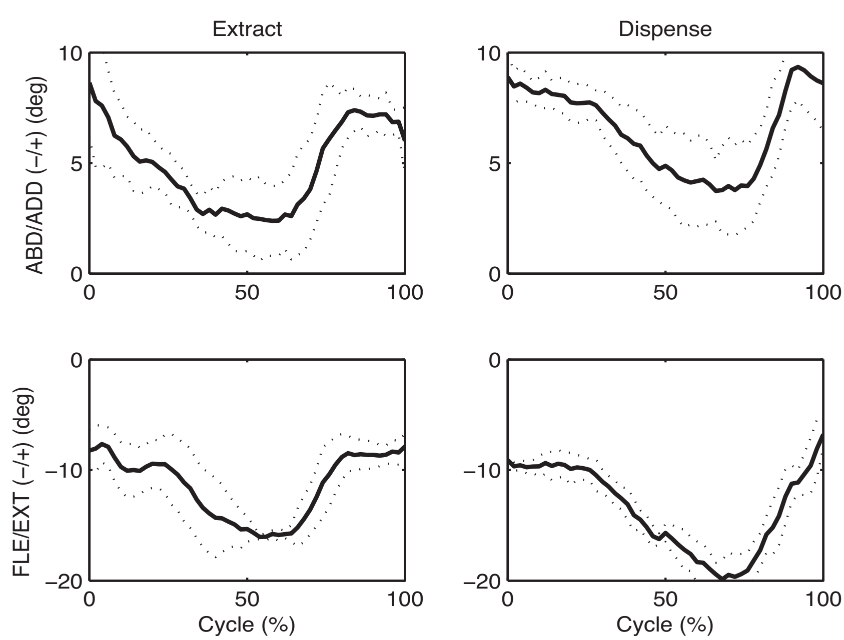

Fig. 3. Representative MP joint angles as a function of work cycle. Left column: extraction cycle. Right column: dispensing cycle. Solid lines – mean; dotted lines – standard deviation.

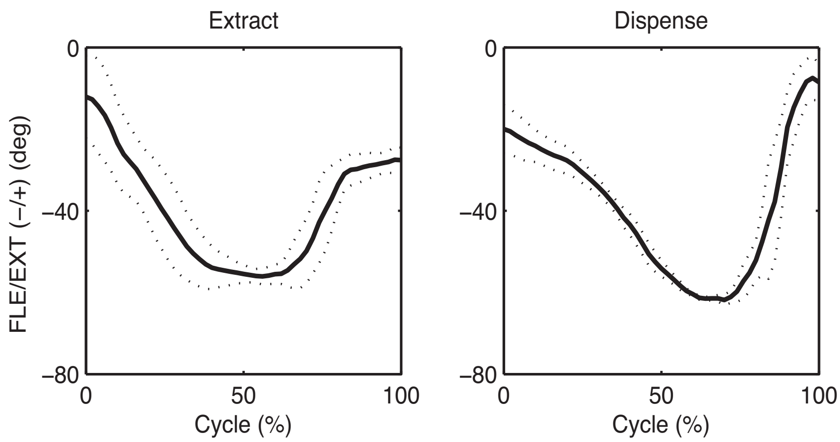

Fig. 4. Representative IP joint angles as a function of work cycle. Left column: extraction cycle. Right column: dispensing cycle. Solid lines – mean; dotted lines – standard deviation.

cycle, a custom-made audible pacer was set to match each subject's preferred pace, and this guided each subject during a pipetting session.

2.2. Kinematics of pipetting

Kinematics for the thumb, fingers, hand, and forearm were determined using methods similar to those in the previous studies [16–18]. Briefly, three hemispherical, retro-reflective markers (4 mm diameter) were applied to each of the proximal, intermediate, and distal phalanges of the fingers; four markers were applied to the proximal and distal phalanges of the thumb, and to the first metacarpal; three markers were applied to the dorsal hand; and a cluster of four markers was applied to the forearm (Fig. 1A). These 55 markers were tracked at 100 Hz using a 14-camera Vicon Nexus system (Oxford Metrics Ltd., Oxford, England).

2.3. Multi-body dynamic model of pipetting

The hand model was developed on the platform of the commercial software package AnyBody (version 5.0; AnyBody Technology, Aalborg, Denmark) (Fig. 1B). The hand is modeled as a multi-body linkage system and includes four fingers (index, long, ring, and little finger), thumb, and a palm segment. Each of the fingers is comprised of a distal, intermediate, and proximal phalanx, and a metacarpal. The thumb is comprised of a distal and proximal

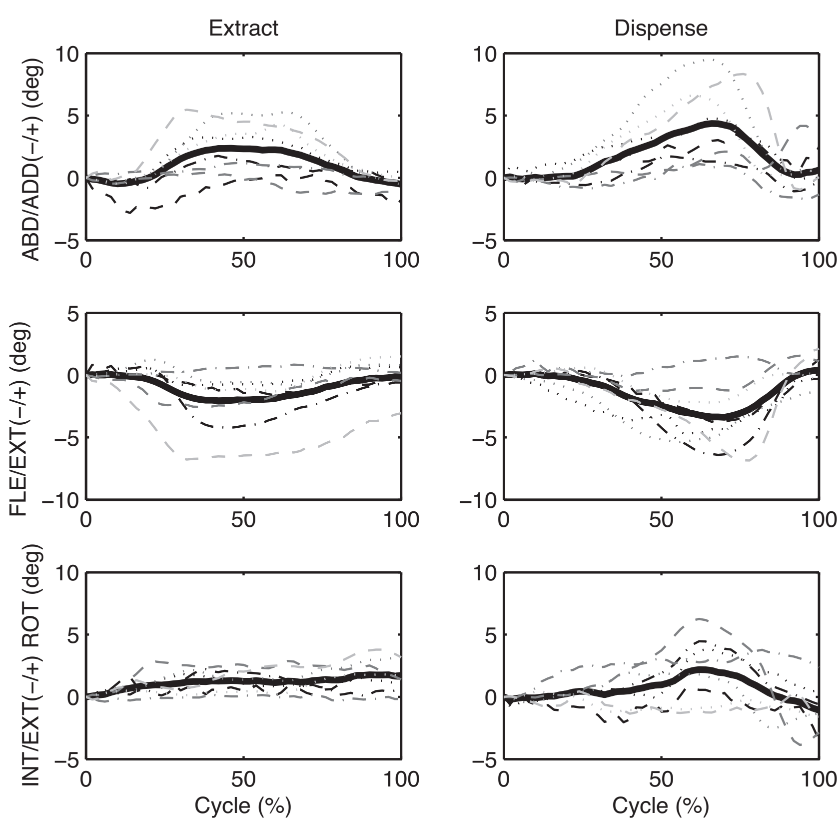

Fig. 5. Ranges of motion of the CMC joint angles as a function of work cycle. Left column: extraction cycle. Right column: dispensing cycle. Thick solid lines – mean; thin lines – eight subjects' data.

phalanx, a metacarpal bone, and a trapezium. The metacarpals of the four fingers and the trapezium of the thumb are considered to be fixed to the palm segment. Consequently, the palm segment includes the scaphoid, lunate, triquetrum, pisiform, hamate, capitate, trapezoid, trapezium, and four finger metacarpals. The four bony sections of each finger were connected by three joints: distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP). The DIP and PIP joints were modeled as hinges with one degree of freedom (DOF) (flexion/extension), whereas the MCP joint was modeled as a universal joint with two DOFs (adduction/abduction and flexion/extension). The four bony sections of the thumb are linked via interphalangeal (IP), metacarpophalangeal (MP), and carpometacarpal (CMC) joints. The IP joint is modeled as a hinge with one DOF (flexion/extension), the MP is modeled as a universal joint with two DOFs (adduction/abduction and flexion/extension), and CMC joint is modeled as a spherical joint with three DOFs (internal/external rotation, adduction/abduction, and flexion/extension).

Since the current study is focused on the thumb, the model includes only nine muscles that are attached to the thumb via tendons: flexor pollicis longus (FPL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), abductor pollicis longus (APL), flexor pollicis brevis (FPB), abductor pollicis brevis (APB), the transverse head of the adductor pollicis (ADPt), the oblique head of the adductor pollicis (ADPo), and opponens pollicis (OPP). The terminology describing the muscles is adapted from [19]. A muscle-tendon unit was modeled by a cord and the muscle-tendon excursion was the length variation of the cord. The OPP and ADPt tendons will have variable wide, flat cross sectional areas and will be attached to bony sections via a narrow flat region rather than a point. These two tendons cannot be adequately represented using a single cord. In the proposed model, the OPP and ADPt tendons are modeled using three and four cords, respectively. The excursions in the OPP or ADPt tendons are evaluated using the averaged excursions of the multiple tendon cords. The muscle-tendon attachment locations and other details of the thumb model have been described in a previous study [20]. The 3D bony meshes were obtained from CT scanning of plastic cadaveric specimens and the 3D mesh of the pipette was created using SolidWorks (Dassault Systemes SolidWorks Corp., MA, USA). The lengths of each bone mesh were scaled to fit the required phalanx lengths in the model.

2.4. Analysis procedure

The time-histories of each joint angle were applied as input data, whereas only the corresponding time-histories of the tendon displacements in the thumb were predicted. The hand model was scaled to the dimensions of each individual subject. The data obtained from the eight subjects were then averaged and the standard deviations were calculated.

The test and calculation results, i.e., the joint angles and tendon displacements, were collected as time series data. The time series data were then processed to be expressed as a function of work cycles [16]. We consider a work cycle as the time period from the start of extraction to the completion of dispensing. The entire time duration for a pipetting work cycle is divided into extraction and dispensing cycles, during which the pipette plunger moves a distance of 12 mm and 18 mm, respectively. In the calculation of the joint motion range and the tendon displacement, the joint angles and the tendon lengths at the start of a work cycle were considered as references. After completing one work cycle, the subjects return to the start of a new work cycle. Because the posture at the end of dispensing cycle (100%) is the same as that at the start of the extracting cycle (0%), the joint motion range and tendon displacement will be zero at 0% and 100% of the work cycle.

3. Results

Subjects' postures during pipetting are quite different, resulting in great scattering in the collected data of the time-histories of the joint angles of the thumb. CMC, MP, and IP joint angles of a representative subject as a function of work cycles are presented in Figs. 2–4, respectively. The left and right columns of the plots (Figs. 2–4) show the joint angles in the extraction and dispensing cycles, respectively. The mean values are shown in solid lines, whereas the standard deviations of the data are shown in dotted lines. For this particular subject, the pipetting actions were accomplished primarily by using the joint motions of MP (Fig. 3) and IP (Fig. 4); the motions in CMC (Fig. 2) were relatively small, especially

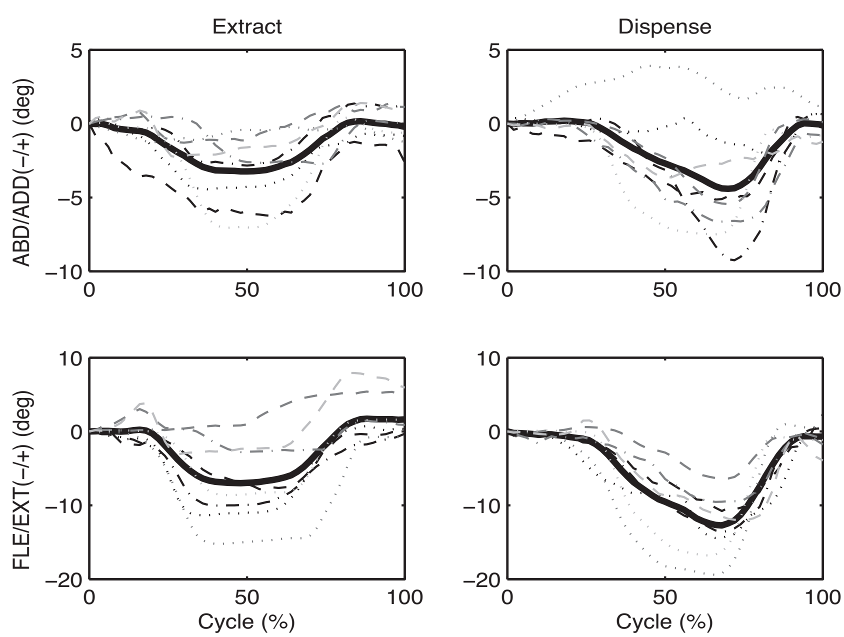

Fig. 6. Ranges of motion of the MP joint angles as a function of work cycle. Left column: extraction cycle. Right column: dispensing cycle. Thick solid lines – mean; thin lines – eight subjects' data.

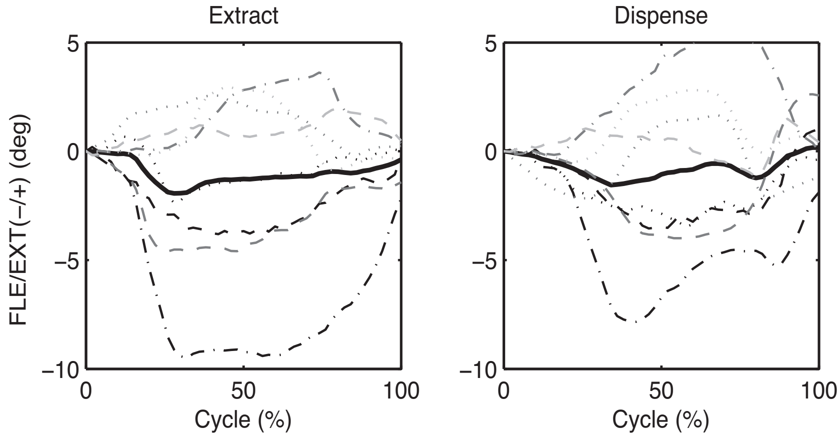

Fig. 7. Ranges of motion of the IP joint angles as a function of work cycle. Left column: extraction cycle. Right column: dispensing cycle. Thick solid lines – mean; thin lines – eight subjects' data.

for internal–external rotation. The joint motions of the subjects are highly variable.

In order to make joint motions of different subjects comparable, we calculated the relative motions of each of the thumb joints during pipetting, i.e., the joint ranges of motion. The joint angles at the start of each pipetting cycle were taken as the references in the calculations of the range of joint motions. The ranges of motion of the CMC, MP, and IP joint angles for all eight subjects as a function of work cycles are shown in Figs. 5–7, respectively. The thick solid lines represent the mean of all eight subjects and the dotted lines are the data of eight individual subject. The left and right columns of the plots show the data in the extraction and dispensing cycles, respectively. Our results show that the patterns of the IP joint motion are quite different among the eight subjects (Fig. 7), whereas the trends of CMC (Fig. 5) and MP (Fig. 6) joint motions for different subjects are relatively consistent.

Tendon displacements as a function of work cycles in APB, APL, and OPP are shown in Fig. 8; those in EPL, FPL, and ADPo are shown in Fig. 9; and those in ADPt, EPB, and FPB are shown in Fig. 10. Again, the left and right columns of the plots show tendon displacements in the extraction and dispensing cycles, respectively. The solid lines represent the mean values of all eight subjects' data and the dotted lines are the standard deviations. Our results indicated generally consistent trends of all nine tendon displacements among all eight subjects. Despite variability in the joint motion data, tendon displacements had relatively small standard deviations.

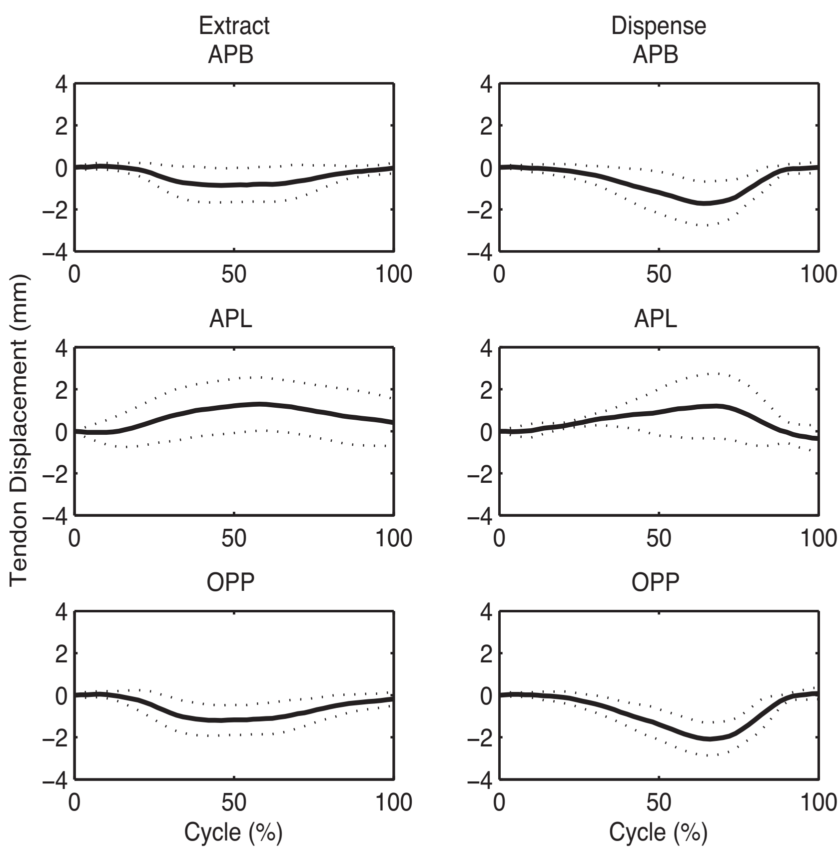

Fig. 8. Displacements of the APB, APL, and OPP tendons during the extraction and dispensing cycles. Left column: extraction. Right column: dispensing. Solid lines – mean; dotted lines – standard deviation.

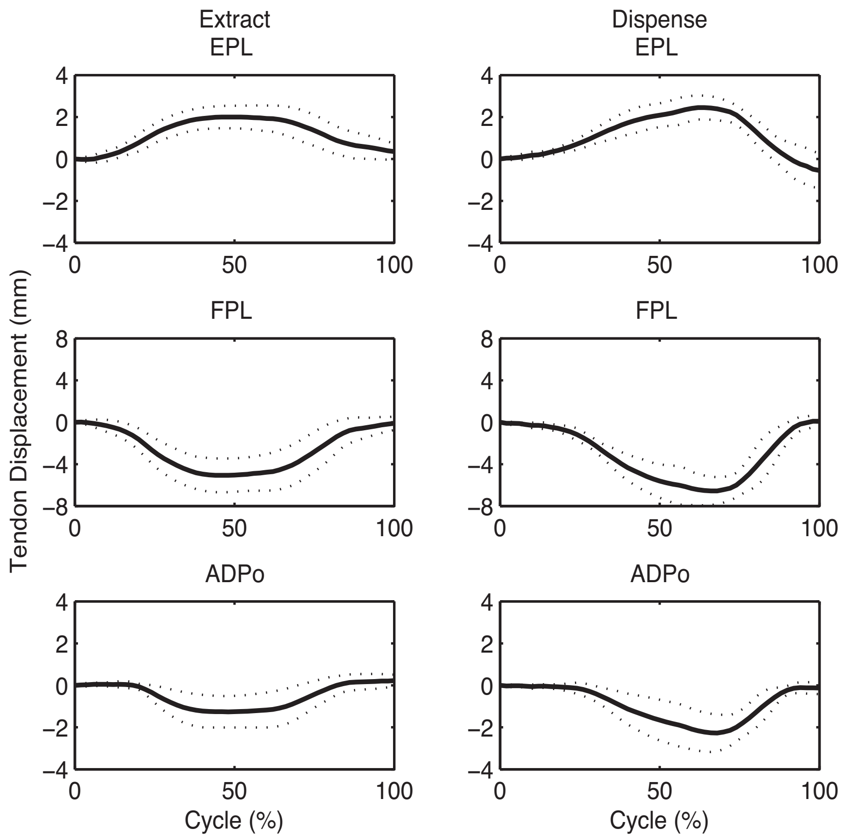

Fig. 9. Displacements of the EPL, FPL, and ADPo tendons during the extraction and dispensing cycles. Left column: extraction. Right column: dispensing. Solid lines – mean; dotted lines – standard deviation.

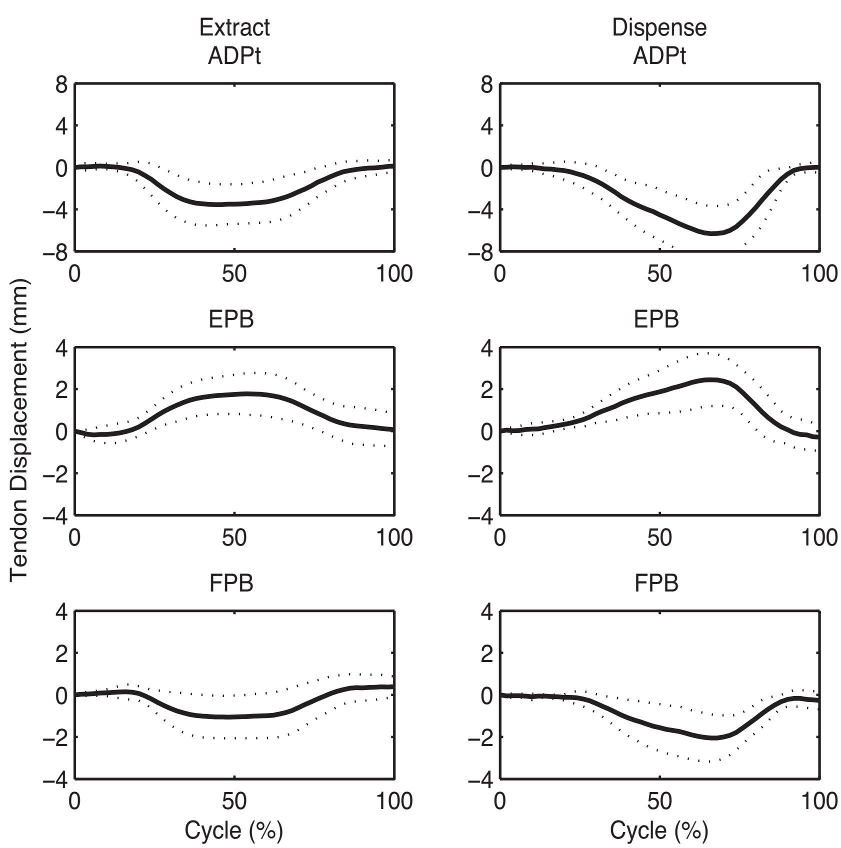

Fig. 10. Displacements of the ADPt, EPB, and FPB tendons during the extraction and dispensing cycles. Left column: extraction. Right column: dispensing. Solid lines – mean; dotted lines – standard deviation.

Table 2
Average pipetting period and accumulated tendon displacements during 1 h for all eight subjects. The accumulated tendon displacements are calculated assuming that subjects' pipetting rates were maintained constant during the pipetting.

Tendon displacement (m)	Subject number								Mean	SD
	1	2	3	4	5	6	7	8		
APB	4.6	6.4	4.2	20.3	3.5	2.7	9.0	6.0	7.1	5.7
APL	3.9	17.8	8.3	12.5	8.3	4.8	14.3	8.1	9.8	4.8
OPP	5.7	8.4	7.2	16.3	5.7	2.6	11.8	9.3	8.4	4.2
EPL	5.6	18.7	8.9	17.7	15.5	8.5	18.3	7.2	12.5	5.5
FPL	11.2	40.6	24.3	44.5	20.7	23.7	46.5	18.2	28.7	13.3
ADPo	5.2	12.0	6.8	18.0	3.7	3.9	16.5	8.4	9.3	5.6
ADPt	17.6	30.8	23.2	46.5	14.3	5.6	36.5	25.5	25.0	13.0
EPB	8.5	20.8	9.2	12.4	11.4	5.8	23.0	9.2	12.5	6.1
FPB	5.5	10.3	5.0	20.9	4.4	4.0	15.4	8.2	9.2	6.1
Work										
Period (s)	4.84	2.12	4.11	2.40	3.52	4.60	2.43	4.60	3.58	1.12
Rate (1/s)	0.21	0.47	0.24	0.42	0.28	0.22	0.41	0.22	0.31	0.11

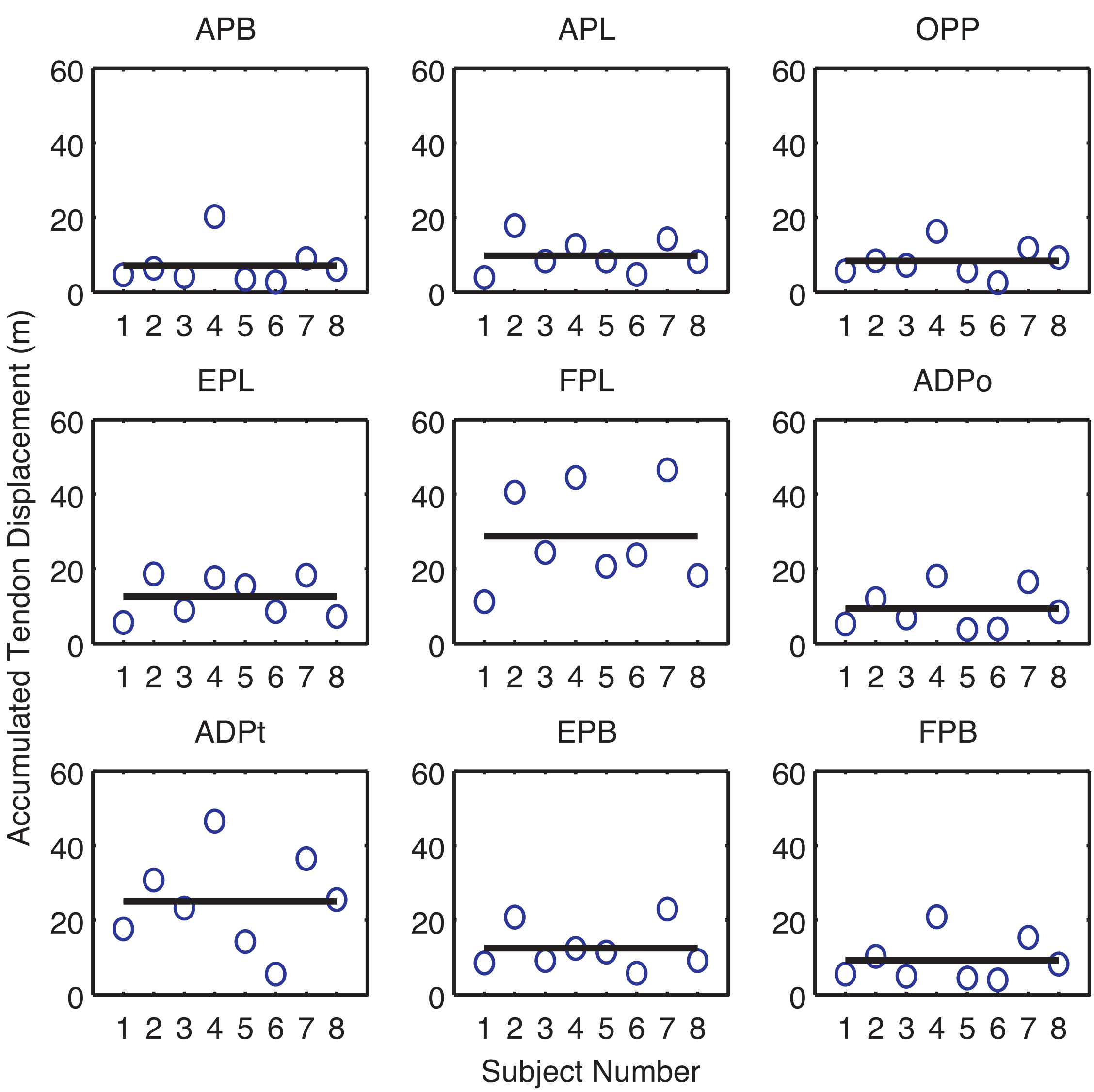

Fig. 11. Accumulated tendon displacements during one hour for all eight subjects, assuming that subjects' pipetting rates were maintained constant during the pipetting. Solid lines – mean; circular symbol – eight subjects' data.

The accumulated tendon displacements during one hour (Table 2) were calculated by the sum of the tendon displacements in the time-histories, assuming that each subject's pipetting rate was maintained constant during a period of 1 h. The accumulated tendon displacement in a work cycle is two times the magnitude of the maximal tendon displacement within the cycle. The average work period of pipetting of individual subjects is also listed in Table 2. The tendon displacement data listed in Table 2 are depicted graphically in Fig. 11. The maximal accumulated displacement was found in the FPL and it reached approximately 29 m.

4. Discussion and conclusion

Since the friction of the tendons on the synovial sheath is believed to be one of the mechanisms of the tenosynovitis [9], the tendon displacement has been applied to evaluate cumulative musculoskeletal disorders in different occupational activities [12–14]. In the current study, we determined the tendon displacement as a parameter to assess the cumulative loading exposure of the musculoskeletal system in the thumb during pipetting. Our study indicated that tendon displacement is advantageous in evaluating the biomechanical loading profile of the thumb compared with other parameters, such as thumb kinematics. The tendon displacements increased with increase in the pipetting rate and hand dimensions (Tables 1 and 2), which are also associated with the joint angles. Our results indicated that the data for the kinematics of the thumb during pipetting were highly variable, since they are dependent on the subjects' hand dimensions, pipetting rate, and postures. Especially, pipetting postures vary substantially among subjects. Most subjects accomplished the pipetting task using the IP motion, whereas some subjects were observed to rely on the CMC and MP motions to accomplish the task, with little IP motion (results not shown). In comparison, the data of the tendon displacements are relatively consistent and contain fairly small standard deviations (Figs. 8–10), despite the highly variable thumb kinematics data (Figs. 5–7).

Despite strong evidence that indicates the use of manual pipetting is associated with the MSDs in the upper extremity, there are no guidelines for safe daily exposure for manual pipetting. Sommerich et al. [12] have tried to establish guidelines of safe exposure for typing jobs based on the cumulative tendon displacements. Previous studies of the MSD risk classification suggested daily accumulated tendon displacement limits to be between 55 m (low risk) and 145 m (high risk) [12]. Although it would not be appropriate to directly use these data to assess the MSD risk of the pipetting task, they do, at least, provide a reference for a comparison. Our results indicate that the maximal tendon displacements were found in FPL for pipetting and the hourly accumulated tendon displacement reached approximately 29 m on average (data ranged from 11.2 m to 46.5 m). If we consider that lab technicians use pipette 2–3 h on a daily basis, the tendon displacements in pipetting would be comparable to those in typing [11] or nailing [14].

If the tendon displacements of typing jobs are considered as references, it would take three hours of continuous pipetting daily for an average operator's MSD risk to reach the medium risk level (i.e., accumulated tendon displacement between 55 m and 145 m). Even for the subject with the highest tendon displacements (i.e., Subject #4 – ADPt and Subject #7 – FPL, Table 2), it would take 2 h of continuous pipetting on a daily basis for the operator to reach a medium risk for MSDs. A direct comparison of the accumulated tendon displacements during pipetting with those who type seems to underestimate the MSD risk in the hand, considering the epidemiological observations of high prevalence of the MSDs in the hand among workers who use pipettes more than 1 h daily [6]. This is because the tendon forces of the thumb in pipetting are substantially greater than those in typing. The maximal push forces at the thumb tip during pipetting [16] are over ten times those at the fingertip during typing [21]. Both tendon/sheath sliding and contact force would contribute to the friction between tendon and its sheath, leading to the tenosynovitis.

In summary, we determined the kinematics and tendon displacements during pipetting in the current study. The maximal tendon displacement during pipetting was found in the FPL tendon. The average hourly accumulated tendon displacements in the FPL during pipetting was estimated to be 28.7 m (11.2–46.5 m), which was in a range of those observed in other occupational activities, such as typing and nail gun operation. Our results showed that the tendon displacement data contain relatively small standard deviations despite the highly variable thumb kinematics, suggesting that the accumulated tendon displacement may be used as a suitable parameter to evaluate the musculoskeletal loading profile.

Disclaimers

Mention of product and/or company name does not imply endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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None.

Ethical approval

Study protocol "Upper extremity biomechanics during the use of hand tools" (ID: 09-HELD-02XP) was approved by the NIOSH HSRB (Human Subjects Review Board, National Institute for Occupational Safety and Health).

Conflict of interests

None declared.

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