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Sensors and Robotics

Evaluation of individual finger forces during activities of daily living in healthy individuals and those with hand arthritis

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ABSTRACT

Introduction: Measuring finger forces during activities of daily living and how these forces change for individuals with pathologies such as arthritis is valuable to our understanding of hand function.
Purpose of the Study: The purpose of this study was to determine the forces of individual fingers during the performance of daily activities in healthy participants and determine the envelope of these applied forces.
Methods: This is a cross-sectional study investigating twenty-five healthy participants (12 female: 22-65 years old and 13 male: 20-53 years old) and participants with osteoarthritis (12 female: 52-79 years old and 9 male: 64-79 years old) examined at one time point. The force sensors were calibrated for each individual using a load cell to provide force output in Newtons. Each participant performed 19 activities of daily living two times. Force was plotted over time for each task, and the maximum force in each finger during that task was evaluated.
Results: The range of applied forces was 1.4 ± 0.6 N to 34.8 ± 1.6 N for healthy participants and 2.3 ± 1.0 N to 30.7 ± 3.7 N for those with osteoarthritis.
Discussion: Sensors allowed for real-time monitoring of finger forces during tasks of daily life. This provides the opportunity to isolate hand grips based on finger recruitment and provide information about the magnitude of forces during the activity.
Conclusion: Measurement of individual finger forces can provide more accurate biomechanical models of the hand and determine the effect of disease on hand functions.

Introduction

The human hand is our primary tool for mechanical interaction with the world. Previous studies have estimated that during a typical 8-hour work day (for a housemaid and a machinist), an average worker performs between 4000 and 5000 grip changes.[1] Our hands are complex end effectors made up of many bones, muscles, tendons, and ligaments allowing for more than 20° of freedom allowing us to perform very precise movements and also exert high forces.[2]

Impairment to the fingers as a result of trauma, autoimmune diseases, and degenerative diseases greatly impede our ability to perform functional tasks.[3] In addition to a reduction in dexterity of the fingers, these impairments often result in pain whenever force is applied to the hands. Hand osteoarthritis (H-OA) is one of the leading causes of decreased hand function in adults and is the most common disease of the hand affecting more than 20% of the population.[3-9] Unfortunately, H-OA has significant consequences including pain, loss of grip strength, and limitations in hand function and participation. Mechanical loading is

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believed to play a role in the development and progression of osteoarthritis.[10] Biomechanical models of the hand can be used in finite element analysis modeling to perform stress/strain analysis or in multibody segment simulation, which enables inverse dynamic modeling and force-dependent kinematic measurement to provide insight into normal and pathological biomechanics. Current models of the hand, however, are difficult due to the complex anatomy of the hand and are lacking in their ability to accurately model mechanical interactions.[11] Many of these models rely on theoretical values of applied loads, and some rely on simple dynamometer measures of grip and pinch strength which do not accurately represent real world interactions.[2] These models of the hand would be greatly improved by the direct measurement of forces applied to the hand during function.

Many measurement systems used to measure hand forces do not directly measure these forces during activity. The most commonly reported measures of hand forces are dynamometer-based measurements of grip strength or pinch strength that quantify the maximum potential of force application.[12] These measures provide little insight into the forces required to complete various activities and do not allow for the measurement of individual fingers.[13] In addition, much work has been carried out to measure finger forces during specific activities by using instrumented objects (strain gauge/load cell) to measure applied loads exerted on objects while performing the functional tasks.[14,15] While this method allows for noninvasive and unobtrusive measurement of individual finger loads, it does not accurately represent real world activity and is limited in the types and amount of functional tasks examined/performed. Alternatively, individual finger forces can be measured using force transducers that are attached directly to the finger. This, however, creates the issue of altering the contact between the volar surface of the hand and the surface being grasped and is not representative of the natural grip.

Pressure Profile Systems has created tactile sensors “Finger Tactile Pressure Sensors” (FingerTPS) that minimize these effects by sewing small capacitive sensors into a microspandex material which allow for much more natural motion of the hands. Previous studies measuring hand forces at the finger joint using these sensors have examined healthy participants completing a handful of specific tasks (such as handwriting, performing cardiopulmonary resuscitation, operating laparoscopic instruments during surgery, sport, and operating a drill).[16−19] Although these measures are helpful in understanding forces during specific applications, an analysis of forces during a variety of common activities of daily living (ADLs) is needed.

Purpose of study

The purpose of this study is to use these wearable force sensors to determine the envelope of applied forces during some common ADLs in healthy individuals and those with osteoarthritis.

Methods

Participant recruitment

Sixty participants were recruited to participate in this study. Participants were recruited from flyers posted on the campus, at the Roth McFarlane Hand and Upper Limb Clinic, and in the local newspaper. Individuals with hand injuries or who were younger than 18 years were excluded from participating. Participants self-reported their health status. Participants were considered healthy if they reported having no injury or disease of the hand, such as arthritis. Participants in the arthritic group self-reported having been diagnosed with H-OA. Each participant read and signed a letter of information and consent form, completed the Patient-Rated Wrist and Hand Evaluation (PRWHE), a demographic form, and participated in a dexterity test. Of the sixty participants recruited who performed the dexterity test, 14 were excluded from the finger force study as they were unable to complete the tasks due to pain in their hands. Figure 1 contains a flowchart of the study.

Dexterity test

Because these sensors slip over the fingers and occlude the volar dermis of the hand and interrupt the natural tactile feedback of the fingers, it was of interest to determine the extent to which wearing these sensors altered the wearer's dexterity. To assess the change in dexterity, sixty participants were recruited to complete the NK Dexterity board[20] with bare hands and while wearing the sensors. The dexterity board, shown in Figure 2, consists of small, medium, and large objects such as blocks and spheres. In each subtest, the participant manipulates the large, medium, or small objects.[20−22] Because hand dexterity involves the combination of different hand movements to efficiently manipulate objects, time is used as a measure of dexterity.[20] The order in which these subtests were completed, and if they were completed first with bare hands or while wearing the sensors, were randomized for each participant. Each subtest was completed three times in succession, and the average time was recorded. The average time for all sixty participants was calculated for each subtest, and the time to complete with bare hands and while wearing the sensors were compared to determine the effect of the sensors on hand dexterity.

Forces during activities of daily living

Twenty-five healthy control subjects (12 women: 22-65 years of age, 13 men: 20-53 years of age) and 21 subjects with H-OA (12 women: 52-79 years of age, 9 men: 64-79 years of age) were

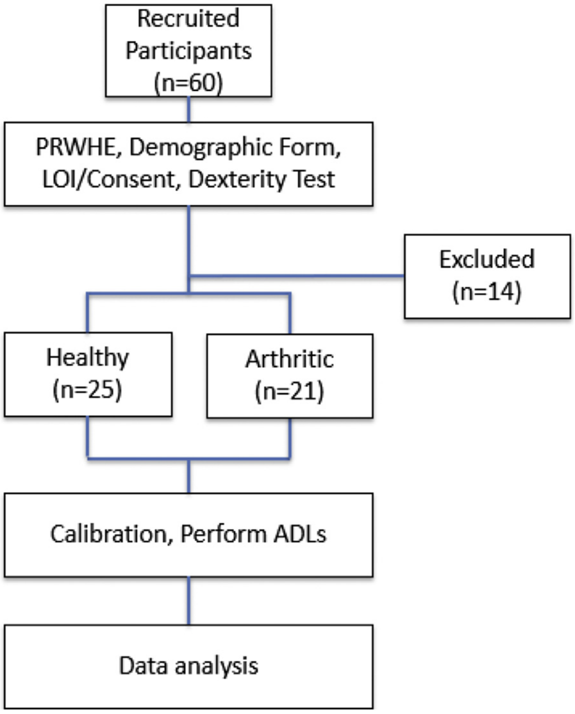

Fig. 1. Flowchart of the study design. ADLs = activities of daily living; PRWHE = Patient-Rated Wrist and Hand Evaluation.

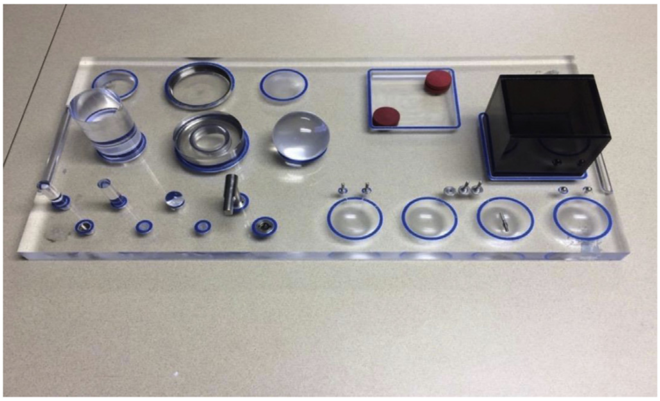

Fig. 2. The NK Dexterity board was used to assess the dexterity of individuals with bare hands and while wearing the FingerTPS sensors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

included in the part of the study. Table 1 contains the demographic information of the participants in each group and their average PRWHE scores. Seventeen representative ADLs involving the hand were examined in this study (Table 2). These tasks were selected from some of the common tasks included in psychometric evaluations for individuals with hand/wrist pain including the PRWHE, Disability of the Arm, Shoulder, and Hand questionnaire, and Joint Protection Behavior Assessment.[23–25] Tasks were selected from various aspects of daily life including kitchen, cleaning, dressing, and grooming tasks. Furthermore, these tasks were selected to include a combination of common power and precision grips to examine the effects of different grips on the forces exerted by the fingers.

Sensor calibration and use

FingerTPS (Pressure Profile Systems, Los Angeles, CA) were used to measure forces during ADLs. These sensors are made up of capacitive sensors which consist of two electrodes separated by a compressible dielectric matrix. As pressure is applied to the sensor, the distance between the electrodes decreases and capacitance increases. These sensors were placed on the thumb and first three fingers (Fig. 3). Each sensor was attached to a signal conditioning wrist module via a single wire and a 3.5-mm connection. This wrist module was connected to a wireless Bluetooth transmitter (D710 electronics interface module; PPS, Los Angeles, CA) clipped to the belt or pocket of the participant, which allowed the participant to move about the room freely during testing (Fig. 4). Capacitance data from each sensor were received on a computer running proprietary Chameleon analysis software via a Bluetooth transceiver.

Before using the sensors to measure force, each TPS sensor was calibrated to allow for the conversion from capacitance to force, measured in newton (N). To calibrate each sensor to measure force, the participant was instructed to press each finger on a load cell (Fig. 5) (PPS, Los Angeles, CA), gradually increasing the force until they reached a force of around 20N. Proprietary Chameleon Testing software (PPS, Los Angeles, CA) then created a calibration equation to convert capacitance values from the sensors to force in N. This process was completed by each participant for each of the sensor at the beginning of testing.

To determine the accuracy of the calibrated FingerTPS sensors, the force output from the TPS sensors was compared with the force output of a clinical finger press load cell (model PF002, NK Upper Extremity Assessment System; NK Biomechanical Corp, Minneapolis, MN) and a Mini45 force/torque transducer (model SI-580-20; ATI Industrial Automation, Apex, NC).

Table 1
Demographic information for participants in the finger force study

Participant	Age	Sex	PRWHE average score (pain/Total)
Healthy (25)	(20-65)	12F: 13M	3/6
Arthritis (21)	(52-79)	12F: 9M	27/49

PRWHE = Patient-Rated Wrist and Hand Evaluation.

Table 2
Tasks of this study

Task Item	Task	PRWHE	DASH	JPBA
1	Fill mug			X
2	Lift mug to mouth			X
3	Carry empty fry pan			X
4	Cut cucumber	X	X	
5	Open water bottle			
6	Lift a 2-L bottle			
7	Open jar		X	X
8	Standard tap			X
9	Lever tap			X[a]
10	Open pill bottle			
11	Push plug into wall			X
12	Spray bottle			
13	Cut with scissors			
14	Write a sentence		X	
15	Standard doorknob	X		
16	Lever doorknob	X[a]		
17	Unlock door with key		X	
18	Button shirt	X		
19	Undo and do up a snap			

PRWHE = Patient-Rated Wrist and Hand Evaluation; DASH = Disabilities of the Arm, Shoulder, and Hand; JPBA = Joint Protection Behavior Assessment.
[a] Task which were listed generically on the evaluation (turning on a tap and turning a doorknob) but were further specified for this study (lever vs standard.)

Data acquisition and analysis

Each subject performed each activity two times in the manner they would usually complete the activity. Including the setup, calibration, and performance of the activities, the total session duration was less than an hour and a half, with each task lasting only a few seconds. Time-stamped force (N) data were sampled at a frequency of 40 Hz. These data were recorded using proprietary Chameleon Testing software (Pressure Profile Systems, Los Angeles, CA). These time-stamped force data were exported to a .csv file, and the custom written code (MATLAB; MathWorks, Natick, MA) was

Fig. 3. Capacitive sensors are located at the fingertips (volar pad) of the thumb and first three fingers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

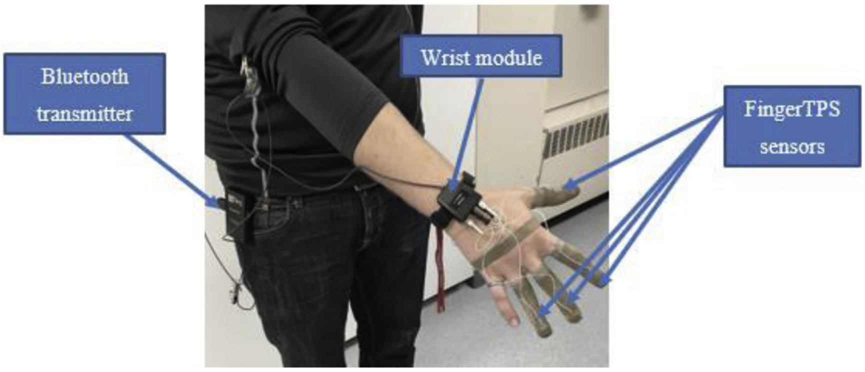

Fig. 4. Complete FingerTPS setup with four sensors (one each on the thumb and first three fingers), wrist module, and Bluetooth transmitter. FingerTPS = Finger Tactile Pressure Sensors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

used to plot the force data over time and extract the peak forces for each finger during each trial (the envelope).

Time-stamped force (N) data were recorded simultaneously from the single degree of freedom load cell and the FingerTPS sensors. The FingerTPS system filtered the signal internally, and the ADC resolution is reported to be 16 bits. No ad-hoc filtering was performed for either measurement system. The time-stamped force data were exported from each program to.csv files, and the custom written MATLAB (MathWorks, Natick, MA) code was used to plot the force over time data for each trial and calculate the difference between both measurement systems as described for each analysis.

Results

Dexterity

In each subtest of the dexterity board, the time that it took to complete the test was significantly greater while wearing the sensors than with bare hands. This difference in time was the greatest in the small subtest, indicating that these sensors impede dexterity more for fine motor tasks. For the large subtest of the dexterity board, the time increased by 1.8 seconds (13%), for the medium subtest 8.2 seconds (31%), and for small 27.6 seconds (41%). This increase in time was statistically significant for each of the three subtests. Figure 6 shows the average times along with standard deviation for the dexterity board.

Fig. 5. Calibration of FingerTPS sensors using provided load cell. FingerTPS = Finger Tactile Pressure Sensors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

There was a strong correlation between the load cell and Finger TPS system in all three trials with $R^2 > 0.9$. The bias or mean difference between the two measurement systems was 0.26 N, −0.39 N, and 0.51 N for each of the three trials, and the limits of agreement were [−2.80, 3.33 N], [−3.52, 2.73 N], and [−3.56, 4.58 N]. For each trial, 93%, 96%, and 93% of the data points fall within the limits of agreement. In all three trials, the agreement between the two measurement systems appears to decrease with the magnitude of the measurement.

Forces during daily tasks

Maximum force during the performance of each task for each sensor was reported to make comparisons in the force data collected. The average maximum force was then calculated for each task and plotted for each sensor location (Figs. 7-9). Standard error bars were used to indicate how far the sample mean is expected to be from the true population mean. Tasks were divided into three groups based on the primary fingers used to generate the force.

Tasks which primarily used the thumb and index finger in a precision grip included plugging in a toaster, opening a water bottle, opening a pill bottle, a snap button, turning a key in a door, buttoning a shirt, and writing a sentence. These tasks are plotted together in Figure 7. The maximum force for these tasks ranged from 9.6 ± 1.0 N to 34.8 ± 1.6 N by the thumb during the shirt button task and the plug-in task, respectively. Furthermore, the smallest peak force was 1.4 ± 0.6 N by the ring finger during the key turning task. For participants with osteoarthritis, the maximum force ranged from 7.9 ± 1.8 N by the thumb during the shirt button task and 30.7 ± 3.7 N by the thumb during the plug in task, whereas the smallest measured peak force was 2.9 ± 0.7 N by the ring finger during the writing sentence task.

Tasks which used a power grip, using all four fingers to apply the force, included pouring a kettle, lifting a mug to mouth, carrying a frying pan, cutting a cucumber, lifting a 2-L bottle, cutting with a pair of scissors, and opening a jar. The average maximum force applied by each finger during these tasks is plotted in Figure 8. The average maximum force for these tasks in healthy participants ranged from 4.4 ± 1.8 N to 19.7 ± 2.7 N by the ring finger during the scissors task and thumb during the cutting cucumber task,

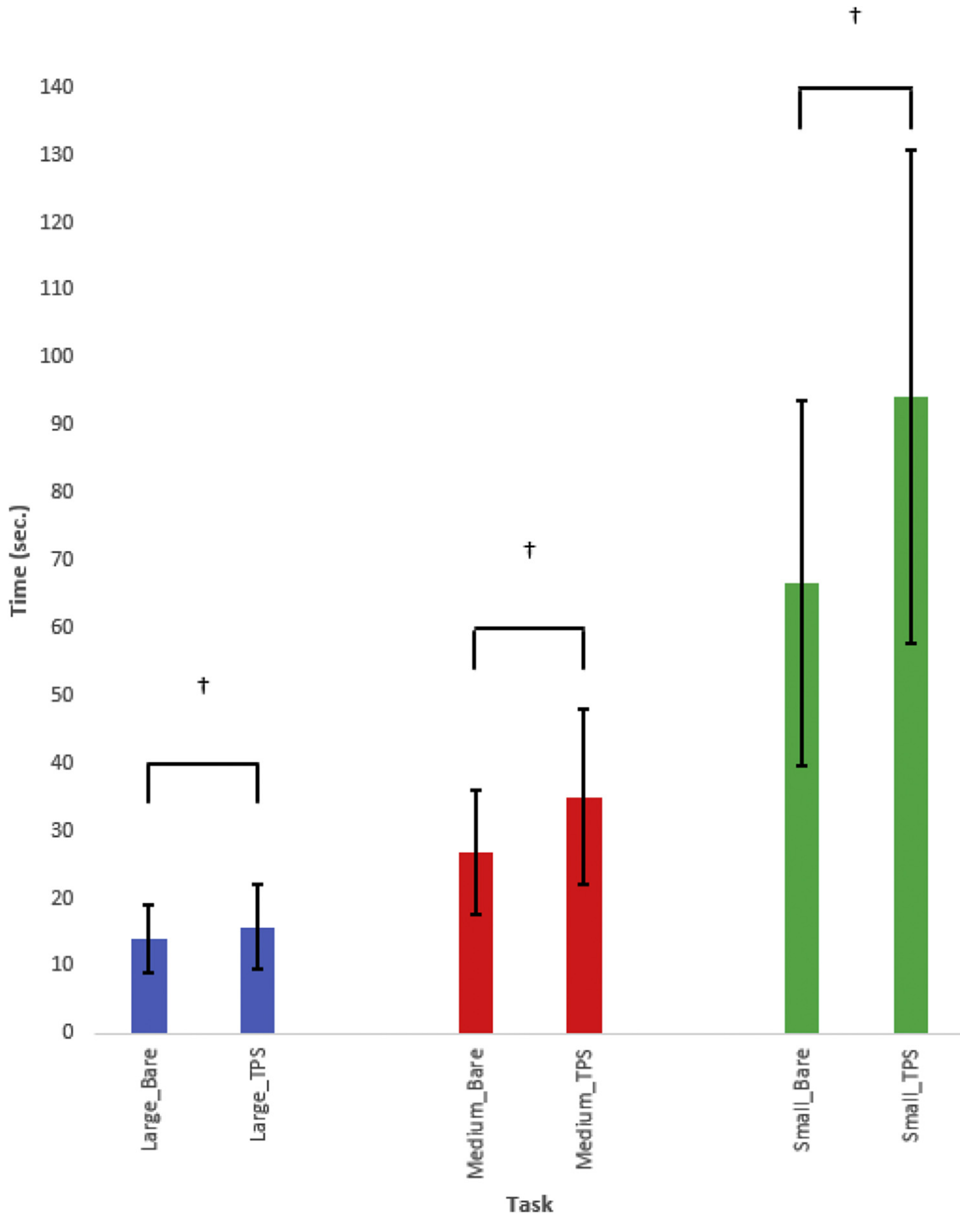

Fig. 6. Average time and standard deviation to complete the dexterity board with bare hands and while wearing the TPS sensors. $n = 60$ participants. † indicates a significant difference from a paired *t*-test. TPS = Tactile Pressure Sensors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

respectively. The lowest peak force for these tasks was 3.2 ± 0.7 N by the index finger during the scissors task. For participants with osteoarthritis, this range was 4.8 ± 1.4 N to 15.4 ± 3.2 N by the index finger during the scissors task and the middle finger during the pouring kettle task, respectively. This lowest peak force for participants with osteoarthritis was 2.3 ± 1.0 N by the thumb during the scissors task.

Tasks which did not clearly fall into either the precision grip between the thumb and index finger or the power grip with all four fingers included the spray bottle and both the standard and lever tap and doorknob. The average maximum forces for these tasks are plotted in Figure 9. The task with the largest magnitude of force for the healthy participants was the standard tap at 13.0 ± 2.5 N by the thumb. However, for participants with osteoarthritis, the task with the largest peak force was the spray bottle which was 16.1 ± 2.7 N by the middle finger.

Discussion

The FingerTPS sensors allowed for the measurement of individual finger forces during the activities examined. They were capable of isolating grips based on finger recruitment for various tasks and providing insight into the magnitude of forces in each finger during activity. The envelope of applied forces during these ADLs in healthy participants was between 1.4 ± 0.6 N and 34.8 ± 1.6 N (in the ring finger when turning a key and the thumb when plugging a cord into an outlet, respectively.) This envelope of forces varied slightly in participants with osteoarthritis. For this group of participants, the envelope of applied forces was 2.3 ± 1.0 N to 30.7 ± 3.7 N (in the thumb during the scissors task and the thumb during the plug in task, respectively.) This envelope, for both the healthy participants and those with osteoarthritis, is consistent with that measured by the Department of Veterans Affairs in a

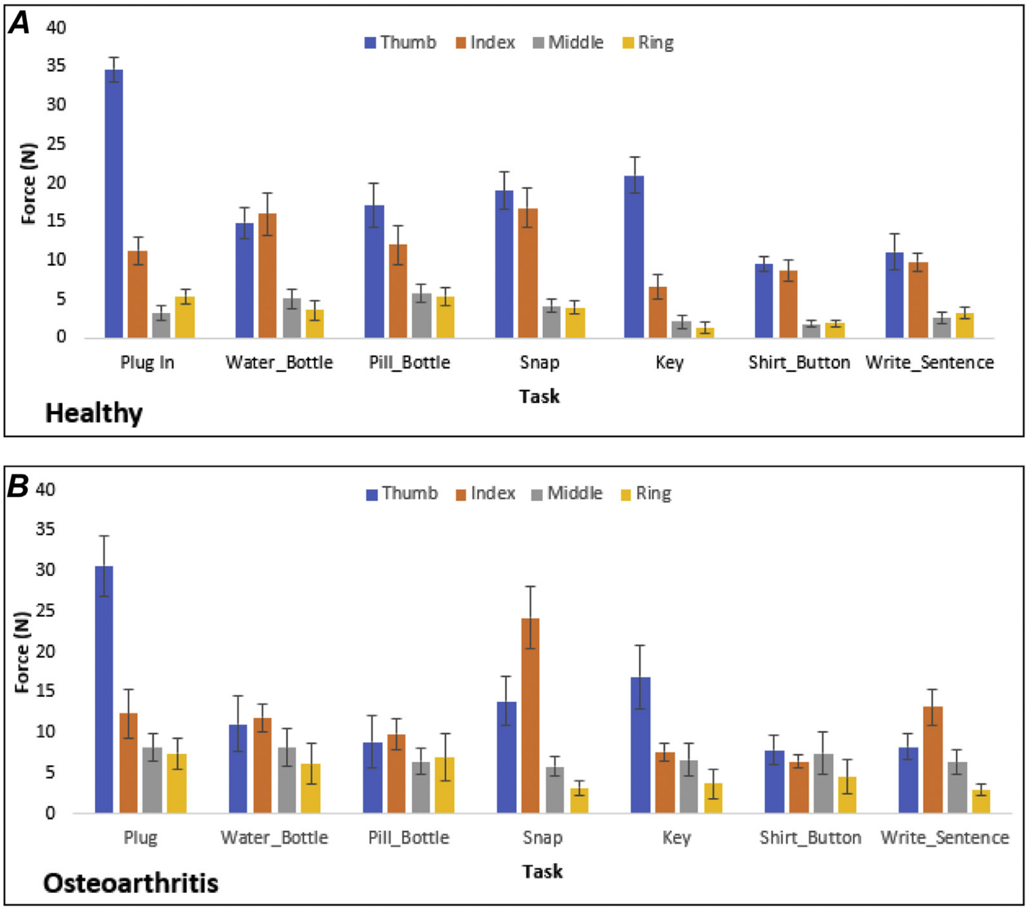

Fig. 7. Max force graphed for each finger in Newtons with standard error for tasks dominated by the thumb and index finger (precision grip). **(A)** $n = 25$ healthy participants. **(B)** $n = 21$ participants with osteoarthritis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

similar study that measured the forces required to complete 12 ADLs. This study reported the envelope to be between 1.4 N and 31.4 N (in a push button remote task and plug in task, respectively).[26]

Compared with published normative pinch strength data for healthy adults, the envelope of applied forces during these activities is lower than the average maximum pinch strength. This indicates that participants are generally able to generate a much higher force than was required to complete ADLs. Werle et al[27] published a study in 2009 which reported normative pinch and grip strength of 1023 healthy adults in 5-year age brackets. In 299 healthy men between the ages of 20 and 64 years, the range of maximum pinch strength was 60.8 N to 134.4 N, with an average of 98.3 N. For the same measure in 304 women in this age bracket, this range was 31.4 N to 122.6 N, with an average of 67.8 N. For men and women combined, the range of maximum pinch strength would be 31.4 N to 134.4 N with an average of 82.9 N.

Dexterity was impeded in each subtest of the dexterity board but was less impeded during the large- and medium-grip tasks when compared with the small-grip tasks. However, all of the activities examined in this study would be classed as large- or medium-grip tasks.

Limitations

There were some limitations found while using the FingerTPS sensors. Since these sensors are propriety and can only be purchased from the manufacturer, they can only be used with their propriety Chameleon Testing Software (Pressure Profile Systems, CA). This greatly decreases the setup time required to use the system and makes the sensors inherently more user friendly, however, does not allow for external validation of the calibration equation generated when calibrating these sensors. Another limitation from the setup used for this study was that we were only able to measure forces at the fingertips, losing valuable information about the applied forces to various finger segments, namely the middle and proximal phalanges of each finger. The manufacturer does sell sensors for these finger segments, and future work should include these sensors. Finally, a limitation of capacitive sensors is their inability to accurately measure forces when shear forces are present. Although many of the activities performed are thought to be primarily normal forces, it is uncertain the extent to which shear forces may have altered the force measurements recorded. This is likely most relevant in tasks such as opening a jar and standard doorknob where torsion is required to complete the activity. In addition to these limitations in the technology, the design of these sensors impeded the wearers dexterity in all three subtests of the dexterity board and the wrist module likely impeded the range of motion of the hand, both of which could potentially impact normal loading of the fingers.

Furthermore, there were limitations in the study design and sampling as well. Although this study sought to select ubiquitous tasks that represent daily life, this study only examined 19 ADLs which may not give an accurate representation of the true envelope of forces. There was a large disparity in age between the two cohorts, with a generally young sample of healthy individuals and

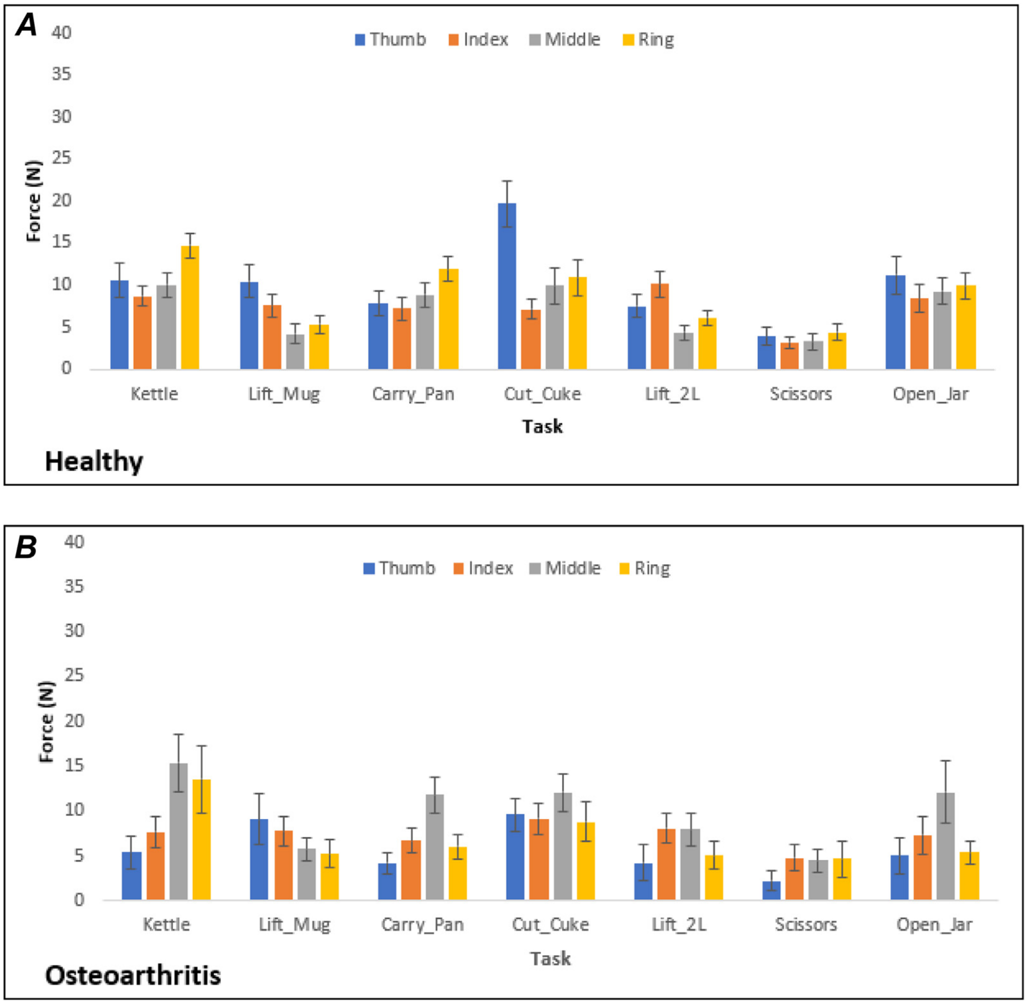

Fig. 8. Max force graphed for each finger in Newtons with standard error for tasks that rely on all four fingers (thumb, index, middle, ring) to generate force (power grip). **(A)** $n = 25$ healthy participants. **(B)** $n = 21$ participants with osteoarthritis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a much older sample of participants with arthritis, which is likely a compounding factor in the difference in force reported as grip strength tends to decrease with age. Furthermore, we did not use a scale to grade and record the type, location, and severity of osteoarthritis present in the individuals with arthritis. As a result of convenience recruitment used to recruit participants for the study, the sample size for both groups was relatively small. Furthermore, many of the individuals with arthritis recruited to participate in the study were unable to complete all of the ADLs due to pain and therefore were not included in the data analysis. As reported, there were 21 individuals with hand arthritis included in this analysis; however, 35 individuals were initially recruited to participate. Fourteen of these individuals were unable to complete many of the ADLs due to pain and were therefore not included in the data analysis. As a result, the reported envelope of applied forces for individuals with hand arthritis does not include those with severe symptomatic OA. In the preliminary stages of this research, we made an effort to include a patient-consumer to determine if the selection of ADLs was appropriate for individuals with arthritis. However, this patient-consumer was high functioning as a result of their arthritis, and in the future, there should be patient-consumers who represent the entire scale of functional ability.

Future work

Further measurements of forces applied by the fingertips would add to the accuracy of current biomechanical models of the hand and measuring the forces in other finger segments would shed valuable insight as well. For tasks which use a hook grasp or similar grasps, the majority of the applied force is exerted by the middle phalanges, and only measuring the finger tips in such activities misses some valuable data.

Unlike the lower extremity that has the standard gait cycle, there is not standard functional assessment that can be used to assess function. In this study, we propose a set of ADLs that are based on current patient reported outcomes and functional assessments and can be used to create a standard "functional assessment" of the hand and upper limb. To limit the effects of coaching on the exertion of force, participants in this study received no instruction on how to perform each activity. However, it is uncertain the degree to which different grips/methods of performing these activities alters the magnitude of force. A thorough analysis of these variations in grip and methods of performance should be conducted. Future work should examine forces applied by the hand during other applications such as recreation, sport, and

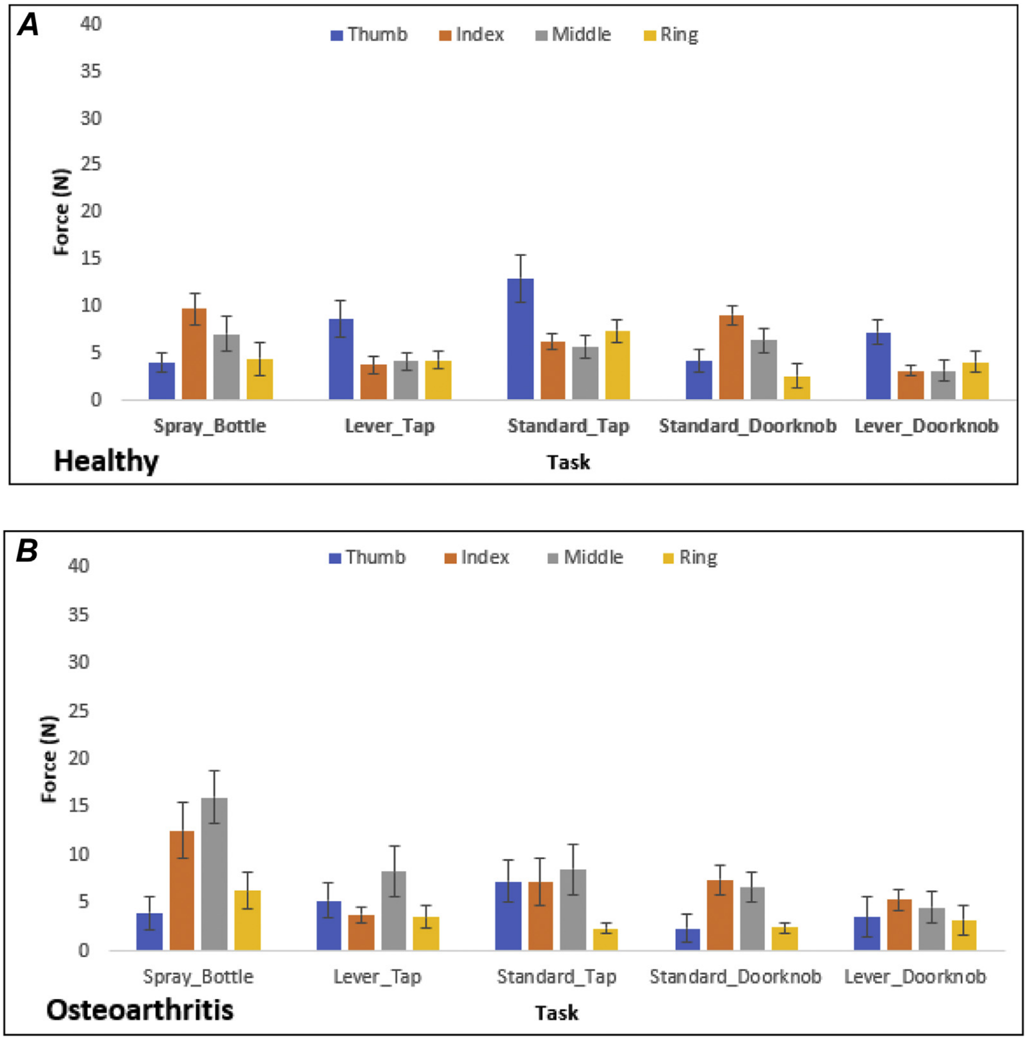

Fig. 9. Max force graphed for each finger in Newtons with standard error for tasks with some other combination of primary movers (power and precision grips). **(A)** $n = 25$ healthy participants. **(B)** $n = 21$ participants with osteoarthritis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vocational (work) tasks. Similarly, the relationship between reduced grip strength and the ability to perform ADLs as well as the applied forces in the hand during these activities should be examined.

Conclusions

Measurement of the magnitude of forces exerted by the fingers during ADLs and how these forces change for individuals with pathologies such as arthritis is valuable to our understanding of how the hands function and how hand function is affected by disease. This study serves as a precursor to a larger study looking at joint protection programs and consists of an initial description of this technology and the development of the possible protocol to be used. This work represents the first step in assessing the effectiveness of joint protection programs at reducing forces for individuals with H-OA. Having examined the normal forces experience during ADLs, researchers can determine, objectively, if enacting key joint protection principles reduces hand forces. In addition, the ability to directly measure these hand forces for individual fingers in a broad array of activities has the potential to greatly improve current biomechanical models of the hand which will, in turn, allow for a greater understanding of the internal joint loading experienced during activity. This study has shown that by using FingerTPS sensors to measure tactile forces, we are able evaluate individual finger forces during ADLs and gain valuable insight into both the magnitude of forces and the recruitment of fingers during activity.

References

1. Dollar AM. *Classifying Human Hand Use and the Activities of Daily Living Activities of Daily living*95. Stanford: Springer Tract in Advanced Robotics Book Series (STAR); 2014.
2. Sancho-Bru JL, Pérez-González A, Mora MC, et al. Towards a realistic and self-contained biomechanical model of the hand. *Theor Biomech*. 2011:211–240.
3. Chen W, Xiong C, Huang X, Sun R, Xiong Y. Kinematic analysis and dexterity evaluation of upper extremity in activities of daily living. *Gait Posture*. 2010;32(4):475–481.
4. Dillon CF, Hirsch R, Rasch EK, Gu Q. Symptomatic hand osteoarthritis in the United States. *Am J Phys Med Rehabil*. 2007;86(1):12–21.
5. Zhang W, Doherty M, Leeb BF, et al. EULAR evidence based recommendations for the management of hand osteoarthritis: report of a task force of the EULAR standing committee for international clinical studies including therapeutics (ESCISIT). *Ann Rheum Dis*. 2007;66(3):377–388.
6. Zhang Y, Niu J, Kelly-Hayes M, Chaisson CE, Aliabadi P, Felson DT. Prevalence of symptomatic hand osteoarthritis and its impact on functional status among the elderly: the Framingham Study. *Am J Epidemiol*. 2002;156(11):1021–1027.
7. Dieppe PA, Lohmander LS. Pathogenesis and management of pain in osteoarthritis. *Lancet*. 2005;365(9463):965–973.
8. Haugen IK, Englund M, Aliabadi P, et al. Prevalence, incidence and progression of hand osteoarthritis in the general population: the Framingham Osteoarthritis Study. *Ann Rheum Dis*. 2011;70(9):1581–1586.

9. Dahaghin S, Bierma-Zeinstra SMA, Ginai AZ, Pols HAP, Hazes JMW, Koes BW. Prevalence and pattern of radiographic hand osteoarthritis and association with pain and disability (the Rotterdam study). *Ann Rheum Dis*. 2005;64(5):682–687.
10. Schick F, Rath B, Eschweiler J, et al. A biomechanical model of the wrist joint for patient- specific model guided surgical therapy: Part 2. *Proc Inst Mech Eng H*. 2016;230(4):326–334.
11. Sancho-Bru JL. A 3D biomechanical model of the hand for power grip. *J Biomech Eng*. 2003;125(1):78.
12. Sevene TG, Berning J, Harris C, Climstein M, Adams KJ, DeBeliso M. Hand grip strength and gender: allometric normalization in older adults and implications for the NIOSH lifting equation. *J Lifestyle Med*. 2017;7(2):63–68.
13. Yeo JC, Lee C, Wang Z, Lim CT. Tactile sensorized glove for force and motion sensing. IEEE SENSORS 2016. Conference Proceedings.
14. Chadwick EKJ, Nicol AC. A novel force transducer for the measurement of grip force. *J Biomech*. 2001;34:125–128. Available at: https://journals-scholar-sportal-.info.proxy1.lib.uwo.ca/pdf/00219290/v34i0001/125_anftftmogf.xml. Accessed November 13, 2017.
15. Fowler NK, Nicol AC. A force transducer to measure individual finger loads during activities of daily living. *J Biomech*. 1999;32:721–725. Available at: https://journals-scholarsportal-.info.proxy1.lib.uwo.ca/pdf/00219290/v32i0007/721_afttmildaodl.xml. Accessed November 13, 2017.
16. Kulothungan G, Nachiappan M, Kumar MS, Rajasekaran S. Comparative study of forces involved in different styles of handwriting. *J Autom Control Eng*. 2013;1(3):260–264.
17. Solevåg AL, Cheung PY, Li E, et al. Quantifying force application to a newborn manikin during simulated cardiopulmonary resuscitation. *J Matern Neonatal Med*. 2016;29(11):1770–1772.
18. Skiadopoulos A, Lango T. Analysis of the pressure exerted by the surgeon' S hand and fingers using a novel robotic laparoscopic instrument during URE-THROVESICAL ANASTOMOSIS. *Soc Am Gastrointest Endosc Surg*. 2016.
19. Sasikumar R, Lenin K. Assessing the influence of hand-arm posture on mechanical responses of the human hand during drilling operation. Int J Adv Manuf T*echnol*. 2017;93(1-4):375–384.
20. Bobos P, Lalone EA, Grewal R, MacDermid JC. Do impairments predict hand dexterity after distal radius fractures? A 6-month prospective cohort study. *Hand*. 2018;13(4):441–447.
21. Turgeon TR, MacDermid JC, Roth JH. Reliability of the NK dexterity board. *J Hand Ther*. 1999;12(1):7–15.
22. MacDermid JC, Mule M. Concurrent validity of the NK hand dexterity test. *Physiother Res Int*. 2001;6(2):83–93.
23. MacDermid JC. Development of a scale for patient rating of wrist pain and disability. *J Hand Ther*. 1996;9(2):178–183.
24. Gummesson C, Atroshi I, Ekdahl C. The disabilities of the arm, shoulder and hand (DASH) outcome questionnaire: longitudinal construct validity and measuring self-rated health change after surgery. *BMC Musculoskelet Disord*. 2003;4:1–6.
25. Klompenhouwer PJ, Lysack C, Dijkers M, Hammond A. The joint protection behavior assessment: a reliability study. *Am J* Occup Ther. 2000;54(5):516–524.
26. Smaby N, Johanson ME, Baker B, Kenney DE, Murray WM, Hentz VR. Identification of key pinch forces required to complete functional tasks. *J Rehabil Res Dev*. 2004;41(2):215–223.
27. Werle S, Goldhahn J, Drerup S, et al. Age- and gender-specific normative data of grip and pinch strength in a healthy. *Hand*. 2009:76–84.

JHT Read for Credit
Quiz: # 672

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\# 1. Units of force were reported in
  a. pounds
  b. foot pounds
  c. newtons
  d. kilograms

\# 2. The force sensors were
  a. readily available commercial models
  b. custom fabricated to meet the needs of this study
  c. in routine use in 10 surveyed hand therapy clinics in Canada
  d. none of the above

\# 3. The protocol called for ________________ as to how to perform the tasks
  a. training of the therapy staff
  b. limited coaching
  c. detailed coaching
  d. no coaching

\# 4. The envelopes for normal and subjects with OA
  a. were not reported
  b. were surprisingly almost identical in both groups
  c. varied slightly in the OA group
  d. varied greatly in the OA group

\# 5. Individuals are generally able to generate more force than is required for typical ADLs
  a. not true
  b. true

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