Abstract

Study Design

Descriptive study, proof of concept.

Background

Our hands constantly handle objects throughout our lives, where a crucial component of this interaction is the detection of grasping (pressure) and slipping (shear) of the object. While there have been a large amount of studies using pressure sensors for grasping detection, synchronised pressure and shear detection at the finger/object interface is still needed.

Objectives

This study aims to assess the feasibility of a sensor system, designed to detect both pressure and shear at the fingertip-object interface via a single subject test.

Methods

One healthy subject participated in the study and was asked to perform a single finger test protocol and a simple hand test protocol. The corresponding multi-directional loads at the fingertip/object interface were measured in real time using a pressure and shear sensor system.

Results

Results from the finger test protocol show peak values of up to approx. 50kPa (5N) and 30kPa (3N) of pressure for each test respectively. Results from the hand test protocol show a pressure and shear profile that shows a large increase in grip force during the initial grasping of the object, with a peak pressure of approx. 50kPa (5N). The pressure and shear profile demonstrates that the load is not evenly distributed across all digits.

Conclusions

This study provides evidence that the reported sensor system has sufficient resolution, dynamic response and load capability to capture biomechanical information during basic protocols and hand-grasping tasks.

Introduction

Human hands display a vast number of movements, gestures, poses and fine motor skills, while constantly interacting with the environment and objects around us. This dexterity is dependent on our ability to sense the environment through touch. Our sense of touch is provided by mechanoreceptors in the glabrous skin (i.e the smooth skin side of the fingertip), with the highest density of these being at the fingertips[1], providing us with an incredibly sensitive array of organic sensors. These provide both somatosensory and proprioceptive feedback, enabling us to perform complex tasks and handle objects in a natural way. Control of finger/object interaction relies on real-time sensing of both pressure and shear, referring to the forces normal and tangential to the fingertip/object interface, respectively, which exist during these tasks. [2, 3] Moreover, the transduction of shear stresses is critical for slip detection and maintaining a stable grasp on an object. [4] Measurement of shear forces would also allow grip compensation before the object slips. The ability to measure dynamic changes in both pressure and shear would facilitate an in-depth understanding of the kinetics at the fingertip/object interface. [5] Such sensing capability, in combination with clinical hand function assessments, [6] could potentially provide a more objective approach and thus aid upper limb rehabilitation in, e.g. stroke patients and amputees. Recognising the long standing need, many works have been reported to evaluate multidirectional forces at the finger-object interface during object or weight handling tasks. This includes the design and exploitation of custom built simulators or handles, where large rigid force transducers were employed at five finger digits. [7-10] However, rigid sensors can affect the contact and interaction between the fingertip and object and thus not suitable for practical hand applications. Vogt et al. [11] reported a soft multi-axis sensor based on microfluidic principles. However, these sensors are much larger (i.e. 50mm x 60mm x 7mm) than the area of a finger tip and also require complex fabrication procedures. No participant based results were reported using these microfluidic sensors[11]. Thus, there is an unmet need to develop a fingertip interface sensor system which not only can measure multidirectional forces during object handling, but also utilises thin and flexible sensor units to allow direct applications at finger and object interface during dynamic hand actions.

This paper presents a novel pressure and shear sensor system, which is capable of measuring three-directional forces. The primary aim of this paper is to study the feasibility of this sensor system to detect multi-directional mechanical interaction at the fingertip/object interface during daily actions such as a single finger touching surface, and a hand action. In particular, for the hand test protocol, we adopted a simple grasp and lift hand action using a cube shaped object. Similar hand actions have been previously reported in evaluating prosthetic hand function using the Southampton Hand Assessment Procedure (SHAP). [6]

Method

Subjects

A healthy volunteer (male, 28 years) with no known hand function deficiencies, took part in an experiment to provide preliminary hand testing data for this study. This study was approved by the University of Southampton Ethics and Research Governance Committee, with submission ID: 20847.

Apparatus

The sensor system comprises a flexible capacitive based sensor of dimensions of 10mm x 10mm in area and a thickness of 1mm. The sensor output is captured by a small data acquisition device and data is transmitted wirelessly via Bluetooth, as shown in Figure 1(a). Sensors were placed at the fingertips to collect real-time pressure and shear data during two specific test protocols. Sensor system design details and calibration are detailed elsewhere.[12, 13]

Procedures

First, a finger test was designed and implemented by mounting a single sensor to the face of the index finger on the subject’s right hand, shown in Figure 1(b). The subject was then asked to repeatedly perform a press-drag-lift action and a press-push-lift action on a hard surface, respectively, at the subject's natural speed and a self-selected force. These one-finger protocols were designed to provide an initial insight into the pressure and shear ranges at the finger/object interface during very basic tasks. For instance, a press-drag-lift action could occur when a finger interacts with a touch screen or feeling the texture of a surface. A press-push-lift action could occur when a finger operates a laptop touchpad or pressing a light switch. For the press-drag-lift action, the finger was dragged in the lateral direction, i.e. dragged from the subject's left to right, aligning with the positive shear X ($+S_x$) direction as shown in Figure 1(b). For the press-push-lift action, the finger was pushed in the longitudinal direction, i.e. pushing away from the subject, aligning with the positive shear Y ($+S_y$) direction shown in Figure 1(b).

The hand test protocol involved mounting five sensors to the faces of all five fingertips of the subject's right hand. The subject was asked to repeatedly perform a simple grasp-lift-hold-put down action on a square block which was approximately 0.8kg in weight and measured 60mm x 60mm x 75mm, as shown in Figure 1(c). This activity was chosen as it utilises the tripod/power grip, one of the most common actions our hands perform on a daily basis. [6]

Data Analysis

Synchronous pressure (P) and shear (S_x and S_y) data from all these tests was collected and analysed as a function of time. Standard deviation (SD) values were calculated over 5 cycles for the peak values of pressure, S_x and S_y, respectively.

[insert Figure 1]

Figure 1(a): Sensor system overview and sensor dimensions, (b): Sensor attached to the right hand index finger, showing directions of pressure, $+S_x$, and $+S_y$ for the finger test actions (c): Sensors attached to the right hand, showing directions of pressure, $+S_x$, and $+S_y$ for the thumb *sensor and the other four fingers, respectively, for the hand test action, i.e. grasping and lifting the block.*

Results

One finger Test Protocols

Figure 2(a) and Figure 2(b) show the typical pressure and shear response as a function of time during the one finger press-drag-lift and press-push-lift actions, respectively. The insets show the respective directions of finger movement aligning with those for $+S_x$ and $+S_y$.

For Figure 2(a), initial contact was established at t≈0.2s, followed by the press phase, the drag phase and the lift phase, as highlighted in Figure 2(a). During the press phase there is a sharp increase in pressure shown, with S_x and S_y showing a gradual increase. Pressure, S_x and S_y increase to a peak value of approximately 50kPa, 32kPa and 18kPa in the drag phase, respectively. Pressure, S_x and S_y decreased during the lift phase, with pressure showing a sharper decline than S_x and S_y. Over five repeated actions, the SD values for peak pressure, S_x and S_y are 7.6kPa, 3.6kPa and 3.8kPa, respectively.

For the press-push-lift action in Figure 2(b), during the press phase, these is an increase in pressure and S_y, while S_x increased less rapidly. During the push phase, pressure, S_x and S_y increased to approximately 30kPa 10kPa and 24kPa, respectively. S_y shows fluctuations of up to approx. 5kPa during the push phase. During the lift phase, pressure, S_x and S_y decreased. At t≈1.2s, finger contact ceased and pressure, S_x and S_y return to baselines. Over five repeated actions, the SD values for peak pressure, S_x and S_y are 4.9kPa, 2.7kPa and 3.3kPa, respectively.

[insert Figure 2]

Figure 2: Pressure, S_x and S_y measured at the index fingertip when performing (a) press-drag-lift and (b) press-push-lift test.

Hand test protocol

Figure 3(a) to 3(c) show the pressure, S_x and S_y response as a function of time for the grasp-lift-hold-put down action, respectively. In particular, Figure 3(a) shows that the contact was initiated at t≈0.8s, followed by the grasp-lift phase, hold phase and the put down phase, as highlighted in Figure 3. It was observed that pressure obtained from the thumb, index and ring fingers increased at the point of contact, while pressure from the middle and little finger only started to show at t≈1.2s and t≈1.4s, respectively. Throughout the hold phase, pressure from the index, middle, ring and little fingers stabilised while pressure from the thumb decreased from approximately 20kPa to 10kPa. Pressure from all fingers show a decrease until the release of the object at t≈6.3s.

Figure 3(b) shows that S_x obtained from the index finger started to increase at the point of contact and increased to approximately 4kPa, while S_x from the thumb and middle finger started to increase later at t≈1.25s to approximately 6kPa and 1.5kPa, respectively. The ring and little finger show negligible change during the grasp-lift phase. Throughout the hold phase, S_x from the thumb, index and middle finger remained relatively stable, while S_x from the ring and little finger increased to approximately 1kPa and 2kPa, at t≈2s.

Figure 3(c) shows that S_y obtained from the thumb changed from approximately -4kPa at t≈1.2s to 5kPa at t≈1.7s. S_x obtained from the index and middle finger increased to approximately

6kPa and 7kPa, respectively. S_x from the middle finger shows a change of approximately 5kPa of at t≈1.2s, to -4kPa at t≈1.75s. S_x from the little finger shows negligible change during the grasp-lift phase. During the hold phase, S_x at the little finger shows a small change of approximately 1kPa at t≈2.5s, while S_x outputs from all other fingers remained relatively stable. In the put down phase, peak S_y values of 13kPa and 12kPa are shown for the thumb and ring finger respectively. The index and middle finger show peak S_y values of approximately -2kPa and -6kPa, before S_y from all fingers decreased to baseline at t≈6.3s. The total contact time is approximately 5.5s. Over five cycles, the peak pressure SD values are 3.4kPa, 11.7kPa, 12.2kPa, 6.9kPa and 6.0kPa for the thumb, index, middle, ring and little finger respectively. Peak SD values for S_x are 4.0kPa, 2.5kPa, 3.0kPa, 2.1kPa and 1.4kPa. Peak SD values for S_y are 4.8kPa, 6.6kPa, 0.8kPa, 2.3kPa and 3.9kPa.

[insert Figure 3]

Figure 3(a): Pressure, (b): Transverse shear (S_x) and (c): Longitudinal shear (S_y) measured at all five fingertip surfaces, when the grasp-lift-hold-put down action was performed.

Discussion

One finger test protocols

In order to assess the sensor system response, resolution and the timing, output from a single sensor during a press-push-lift and press-drag-lift has been analysed. The profiles and peak values displayed in Figure 2 align with values exhibited by Su et al., [14] where approx. 10N of F_z (pressure) and 5N of F_x and F_y (shear) were observed during a press-drag-lift test, conducted on a force-plate. This indicates that the sensor system is capable of measuring dynamic changes in pressure and shear at the fingertip/object interface, with minimal delay. The resolution of the sensor system is approx. 0.5kPa (approximately 0.05N) for pressure and 0.25kPa (approximately 0.025N) for shear measurements when calibrated up to approx. 100kPa (10N) and 25kPa (2.5N), respectively.[2]

Hand Protocol

The hand protocol was used to examine the sensor systems' capability to capture synchronised data from five fingers and therefore capture the inter-digit coordination during a simple grasping task. Figure 3(a) shows that, during the initial grasping phase, peak pressure values reached approximately 50kPa and 45kPa at the thumb and index finger respectively, equating to approximately 5N of normal force and 4.5N of tangential shear force. These values align with values reported by Landsmeer et al,[15] where approx. 5N of normal force was observed at the index, middle and ring finger and approx. 4-6N of tangential force was observed across all digits, when the hand was lifting an object equating to 10.4N. Furthermore, pressure peaks occur at 0.8s and 0.6s after initial contact at $t \approx 0.8s$. Subsequently, this grip force reduced to approximately 20kPa and 5kPa for the thumb and index finger, respectively, at $t \approx 1.9s$ and sustained at that level throughout the hold phase. The 'over-estimation' of the required grasping force at initial contact has also been observed by others[16, 17] and demonstrates the sensor systems' capability to capture synchronised biomechanical information. During the grasp-lift phase, S_x from the thumb showed a sharp increase, as shown in Figure 3(b) and remained almost constant at approximately 5kPa, while S_x from the remaining fingers showed comparatively lower values, up to 2kPa, throughout the hold phase. This may suggest that, in comparison with the index, middle, ring and little fingers, the thumb sustained a large amount of pressure and shear forces, while securing the object. The importance of the thumb for object handling has also been previously reported.[15, 18] During the grasp-lift-hold-put down action, the majority of shear expected was in $+S_x$ as shown in Figure 3(b); however, shear in $+S_y$

direction was observed with a peak value seen at the thumb interface of approximately 12kPa, as shown in Figure 3(c). The coexistence of S_x and S_y indicates that, although this particular hand action was to grasp and then lift the object in S_x direction; at each fingertip, there was a combination of multidirectional forces, reflecting the complex and dynamic interactions between fingers and the object.

In order to study the time difference and coordination among different fingers during the grasp-lift-hold-put down action, results have been analysed from the thumb, index and middle finger, respectively, because the results in Figure 3 indicate that these three digits are more dominant for this action. Contact between the subject's hand and the object was initiated by the index finger at initial contact, when pressure obtained from the index finger started to increase, as shown in Figure 3(a). Initial contact by the index finger has been commonly observed and reported.[19] It was only after the subject has begun to lift the object, that the middle finger was recruited to help grasp, thus the increase of pressure to 6kPa. This grasp adjustment during this task has been previously observed by Flanagan.[16] Fluctuations in shear were observed at the thumb, index and middle finger, which could be attributed to the subject stabilising the block during the put down part of the action.

Conclusion

A dynamic, real-time pressure and shear sensor system for the fingertip/object interface has been deployed in preliminary tests using a healthy subject, as a proof of concept. Both the one-finger and the hand test protocols were conducted to perform a finger press-drag-lift and press-push-lift tests on a surface, as well as a hand grasp-lift-hold-put down action on an object, with a view to measuring pressure, transverse shear and longitudinal shear at the fingertip/object interface during these typical hand tasks. The ability to measure real-time pressure and shear at the fingertip/object interface could lead to a deeper understanding of the finger and hand kinetics during daily hand tasks. This biomechanical information could also be used to provide an objective hand-function assessment tool, which could be potentially exploited to assist upper limb rehabilitation. It is worth noting that the primary aim of this study is to demonstrate the feasibility of the developed interface sensor system for fingertip-object applications. As such, proof of concept tests with a single subject have been presented. This leads to inevitable limitations for the assessment of fingertip and hand biomechanics.

The presented results suggest that the sensor system is sensitive enough to detect dynamic changes in pressure and shear at the fingertip-object interface during basic object handling actions. The results are encouraging and suggest that the sensor system could be potentially used for applications such as, providing tactile feedback for prosthetic hand users and to facilitate biomechanical studies as a research tool in combination with existing hand functional assessments, e.g. SHAP.[6]

For future work, this study would benefit from tests with a variety of daily hand actions, such as lateral grip actions, inclusion of objects with different weight and shape, as well as tests involving multiple participants including those with hand deficiencies and users of prosthetic hands. This would give an insight into biomechanical interaction at the fingertip/object interface during daily hand actions.

Manuscript Word Count: 2668

Acknowledgements

The authors would like to thank the UK Engineering and Physical Sciences Research Council (EPSRC), Medical Research Council (MRC) and the China Scholarship Council (CSC) for providing funding. Supporting data is openly available from the University of Southampton repository at http://dx.doi.org/10.5258/SOTON/xxxxx.

Conflict of interest

None declared.

Author Contribution

All authors contributed equally in the preparation of this manuscript.

Reference

1. Johansson RS and Vallbo AB. Tactile Sensory Coding in the Glabrous Skin of the Human Hand. *Trends Neurosci*. 1983; 6: 27-32.
2. Yousef H, Boukallel M and Althoefer K. Tactile sensing for dexterous in-hand manipulation in robotics—A review. *Sensors and Actuators A: Physical*. 2011; 167: 171-87.
3. Codd R. Development and Evaluation of adaptive control for a hand prosthesis. *Department of Electronics*. Southampton, UK: University of Southampton, 1976.
4. Kao I and Cutkosky MR. Comparison of Theoretical and Experimental Force/Motion Trajectories for Dexterous Manipulation with Sliding. *Int J Robot Res*. 1993; 12: 529-34.

5. Dellon B and Matsuoka Y. Prosthetics, exoskeletons, and rehabilitation [Grand Challenges of Robotics]. *IEEE Robotics & Automation Magazine*. 2007; 14: 30-4.

6. Light CM, Chappell PH and Kyberd PJ. Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Archives of physical medicine and rehabilitation*. 2002; 83: 776-83.

7. Li ZM. Inter-digit co-ordination and object-digit interaction when holding an object with five digits. *Ergonomics*. 2002; 45: 425-40.

8. Zatsiorsky VM, Gao F and Latash ML. Prehension synergies: effects of object geometry and prescribed torques. *Exp Brain Res*. 2003; 148: 77-87.

9. Pataky T, Latash M and Zatsiorsky V. Tangential load sharing among fingers during prehension. *Ergonomics*. 2004; 47: 876-89.

10. Chen P-T, Lin C-J, Chieh H-F, Kuo L-C, Jou IM and Su F-C. The repeatability of digital force waveform during natural grasping with five digits. *Measurement*. 2016; 85: 124-31.

11. Vogt DM, Park Y-L and Wood RJ. Design and Characterization of a Soft Multi-Axis Force Sensor Using Embedded Microfluidic Channels. *IEEE Sensors Journal*. 2013; 13: 4056-64.

12. Laszczak P, Jiang L, Bader DL, Moser D and Zahedi S. Development and validation of a 3D-printed interfacial stress sensor for prosthetic applications. *Med Eng Phys*. 2015; 37: 132-7.

13. Valero M, Hale N, Tang J, et al. An Interfacial Pressure and Shear Sensor System for Fingertip Contact Applications. *Healthcare Technology Letters*. 2016.

14. Su Z, Fishel JA, Yamamoto T and Loeb GE. Use of tactile feedback to control exploratory movements to characterize object compliance. *Front Neurorobot*. 2012; 6: 7.

15. Landsmeer JM. Power grip and precision handling. *Ann Rheum Dis*. 1962; 21: 164-70.

16. Flanagan JR, King S, Wolpert DM and Johansson RS. Sensorimotor prediction and memory in object manipulation. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*. 2001; 55: 87-95.

17. Nowak DA and Hermsdorfer J. Grip force behavior during object manipulation in neurological disorders: toward an objective evaluation of manual performance deficits. *Mov Disord*. 2005; 20: 11-25.

18. Gonzalez-Sanchez V, Rowson J and Yoxall A. Analysis of finger movement coordination during the Variable Dexterity Test and comparative activities of daily living. *Int J Ther Rehabil*. 2016; 23: 480-90.

19. Johansson RS and Westling G. Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic-Control of Precision Grip When Lifting Rougher or More Slippery Objects. *Experimental Brain Research*. 1984; 56: 550-64.