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Development of a 3-axis Human Fingertip Tactile Sensor with an Ortho-Planar Spring

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Abstract— **Human experts have mastered many manual skills. Transferring those skills to robots or human novices is challenging. Not only the movements, but also the exerted forces are of importance. In this paper we propose a sensor that can measure the force vector acting on the human fingertip, without covering the part of the fingertip that is contact with the touched object. Compared to our previous iterations of this sensor, we use a spring instead of viscoelastic material as the deformable material for the sensor. While it is challenging to include a spring in the given form factor, springs have the benefit of lower hysteresis than viscoelastic materials. This paper presents the integration of the spring in the sensor and shows experimental validation with 8 subjects. Compared to our previous version of the sensor with 2 Hall effect sensors, we achieved improved sensing characteristics.**

I. INTRODUCTION

Human experts have mastered various manual skills. Transferring those skills to robots or human non-experts is challenging. Not only the movement, but also the forces are a necessary component in some Learning from Demonstration (LfD) instances, such as during precise assembly. Therefore, the movements as well as the forces that the human expert utilizes should be recorded. The robot or human novice should be equally equipped with sensors to record the movements and forces, which would enable to monitor, compare, and provide feedback to the robot or human apprentice. Several solutions exist to measure the movements of both humans and robots. However, while many adequate tactile sensors for robots exist, few tactile sensors for humans have been reported, and the existing solutions have shortcomings.

Covering the human fingers with distributed force sensors to directly measure the interaction forces obstructs the expert's performance and is therefore not ideal. In this paper we therefore measure the forces indirectly, by measuring the deformation of the human flesh of the fingertip. By measuring the 3-axis deformation on each side of the fingertip, we can acquire the 3-axis forces acting on the fingertip. In particular, we use two small sized 3-axis Hall effect sensors combined with a magnet each to measure the 3-axis deformation on each side of the fingertip.

We presented a first version of the sensor in [1] and an improved version in [2]. In both previous versions, the magnet was placed relative to the Hall effect sensor by means of viscoelastic silicone. In our experience, also with tactile sensors for robots, the use of such viscoelastic material is not ideal, as it introduces additional hysteresis (in addition to the hysteresis of the fingertip flesh) to the system. The current paper therefore explores the possibility of using a small sized spring instead of viscoelastic material for the sensor. Using a spring in the given form factor is challenging, and we propose the use of an ortho-planar spring. For our first prototype of such a spring, as reported in this paper, we used a 3D printer to produce the spring. Given our successful implementation of the spring in the current paper, future work can implement the spring with metal instead, to fully benefit from the reduced hysteresis. Furthermore, in [2] we propose to use 4 instead of 2 Hall effect sensors, and the benefits of the spring and of using 4 sensors can be combined in future work.

The rest of this paper is organized as follows. Section II reports related work on tactile sensors for human fingers. Section III describes the sensor design. Section IV describes the setup and procedure for the sensor calibration. Section V shows the evaluation results of 8 subjects and discusses the results. Section VI draws conclusions and discusses possible future work.

II. RELATED WORKS

The concept of a wearable tactile sensor was introduced in [3]. The main component of this design is a piezo-resistive tactile sensor that is mounted to the user's fingerpad. In this wearable sensor, the piezo-resistive sensor measures the force directly, which means that the transducer needs to be in direct contact with the object surface in order to measure force. Thus, the user's tactile feeling and sense of touch is hampered, and it feels unnatural for the user to handle an object.

Several methods have been introduced that enable an indirect measurement of the forces exerted by the fingertip. For example, the photoplethysmography principle was used [4] [5]. The measurement is based on the change of the coloration pattern of the fingernail which occurs when force is applied to the fingertip. The sensor consists of photodiodes and LEDs that are glued on the fingernail. The photodiodes sense the change of the fingernail color and then this output of the photodiodes is converted to three axis forces via calibration. Further research focused on the improvement of the calibration system to reduce the error [6] [7] [8] [9].

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Another indirect measurement principle, based on finger pad deformation, was introduced by [10]. This principle exploits the natural characteristic of the human fingertip that the fingertip pulp extends horizontally when force is applied vertically to the fingertip. The research analyzes the relationship between the pulp deformation and the applied vertical force by performing experiments with 20 subjects. Further research in [11] derived a viscoelastic material model for the human fingertip pulp when force is applied to the fingertip. The viscoelastic material model was chosen because the fingertip pulp displays hysteresis and nonlinear characteristics similar to a viscoelastic material. However, only few research has been done to analyze the deformation of the fingertip resulting from shear force [12].

Based on the finger pad deformation principle, a finger tactile sensor has been introduced by [13]. The sensor consists of two small strain gauges which are attached to a lever structure on each side of the fingertip. The horizontal deformation of the fingerpad is measured by the strain gauges. The sensor was mounted on a fingertip and enables the user to directly touch the object without obstruction.

Using the same measurement principle based on finger pad deformation, [14] proposed a wearable device consisting of six photo-reflective sensors surrounding the fingertip. Three sensors face down to the surface to measure the distance to calculate the fingertip posture. The other three sensors facing the front and side of the fingertip measure the skin deformation which was then converted to 3-axis force. The paper states that changes in the ambient light disturb the measurements, and the sensor is considerably wider than our design.

Another approach was introduced by [15]. The sensor consists of flexible Polyvinylidene fluoride (PVDF) wrapped around the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints. The PVDF film exhibits a piezoelectric characteristic and can thereby sense the vibration propagated from the fingertip. Vibrations occur between the fingertip and the object surface when the user is handling an object. As the sensor is mounted between the DIP and PIP joints, the user's fingertip can freely contact the object without obstruction.

In summary, to the best of the authors knowledge, previously proposed finger tactile force sensors either obstruct the human haptic feedback, can be mounted only on the fingertip, or cannot measure 3-axis force.

III. Sensor Design

In this paper we present a new wearable finger tactile sensor based on the same principle (i.e. the finger-pad deformation principle [10]) used in the previous iterations [1] [2]. The new design houses two 3-axis Hall effect sensors (one on each side of the fingertip) adjacent to a 3D printed ortho-planar spring, as shown in Fig. 1. In total, 6 magnetic measurements are taken with constant 90Hz sampling rate to measure the fingertip deformation.

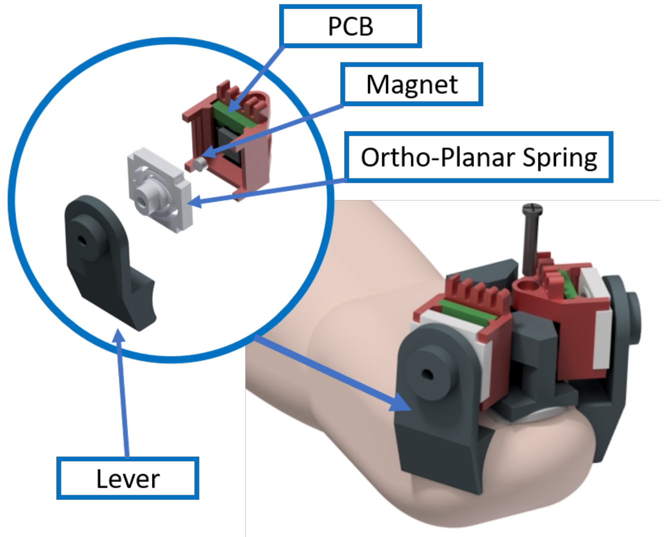


Fig. 1: Exploded view

A. Mechanism Overview

To alleviate the drawbacks from the previous design, a novel lever mechanism is proposed and tested. The mechanism consists of a lever attached to an ortho-planar spring in a cantilever configuration. A permanent magnet (neodymium, grade N50, 1.5mm diameter and 0.8mm thickness) is housed within the spring adjacent to the 3 axis Hall effect sensor. Please refer to the exploded view of the lever mechanism as shown in Fig. 1.

B. Details

In total, the improved fingertip sensor features two levers placed around the fingerpad paired with one 3-axis Hall effect sensor each. Each lever contains a neodymium magnet that is housed axially within the ortho-planar spring as shown in Fig. 1. The north pole of the neodymium magnet faces towards the surface of the Hall effect sensor. The lever is attached to the ortho-planar spring. The structure comprising of the magnet, the lever and the ortho-planar spring is housed within a joint casing. The joint casing is coupled to a linear slot by a simple bolt and nut arrangement, allowing the lever to be adjusted to ensure effective sensor coverage by conforming to the wearer's finger-pad.

Lever: The lever mechanism is designed to conform with the general shape of the human fingertip. By loosening the top bolt as shown in Fig. 1, the user can rotate and adjust the lever to fit to the size and curvature of the fingertip. This ensures effective displacement of the lever by the fingertip. The lever mechanism enables the permanent magnet to be mounted as close as 1mm to the Hall effect sensor. At the same time, it permits a small width of the device on the sides of the fingers.

Ortho-Planar Spring: The ortho-planar spring allows the magnet to be displaced relative to the respective Hall effect sensor. The ortho-planar spring design ensures low hysteresis by bringing the position of the magnet back to its initial position after it was displaced due to the deformation of the finger-pad. The elastic property of the ortho-planar spring enables the lever to displace from its initial position due to the deformation of the finger-pad ultimately displacing the permanent magnet spatially in three-dimensional space. In particular, the movement of each magnet in 3-axis is measured respectively by one 3-axis Hall effect sensor.

Hall effect sensor PCBs: The PCBs in this paper were re-used from our previous work [1] with dimensions 6mm x 6mm x 1.8mm. The main component of each PCB is a MLX90393 3-axis Hall effect sensor from Melexis. Two PCBs were used, one on each side of the fingertip, and they were connected together to a microcontroller as the master using an I2C bus. Only 4 wires were required (3.3V, electric ground, clock, and data) between the microcontroller and the Hall effect sensor PCBs.

IV. Sensor Calibration

Human factors such as the shape and hardness of the fingerpad uniquely characterize the way the fingerpad skin deforms. Furthermore, the precise position of the sensor on the fingertip is not the same, which is why calibrating the finger tactile sensor is essential each time the finger tactile sensor is mounted on a user's fingertip.

The fingerpad deformation displaces the magnet housed within the lever. As a result, the Hall effect sensor gives out raw magnetic measurements corresponding to the displacement of the magnet. The calibration converts these raw magnetic measurements from two 3-axis Hall effect sensors to 3-axis force measurements.

In this paper, we used supervised learning to calibrate the finger tactile sensor. Therefore, a reference sensor is required as part of the calibration setup. When calibrating the finger tactile sensor, both the reference sensor and the finger tactile sensor data are recorded together. Two sets of data samples were taken; calibration data for learning and test data for evaluation. We used a linear model to convert the Hall effect sensor readings to 3-axis force. Due to the non-linear characteristics of the human fingertip we expected that a non-linear calibration model would perform better than a linear model, but in preliminary experiments the linear model produced better results than a quadratic model for forces of less than 10 N, which is why we used a linear model for the current paper.

A. Calibration Setup

To calibrate the finger tactile sensor, linear regression was used to derive a linear relationship between the fingerpad skin deformation and the force applied at the fingertip. Fig. 2 shows the calibration setup, composed of a 6-axis force torque sensor (ATI Nano 17) and an Arduino Due microcontroller with a 16-bit extended ADC shield for Arduino from Mayhew Labs. The 6-axis force torque sensor connected to the ADC shield analog input pins. In this paper, only the 3-axis forces (not the torques) were used for calibration and evaluation of the finger tactile sensor. The finger sensor connected to the Arduino Due's I2C pins.

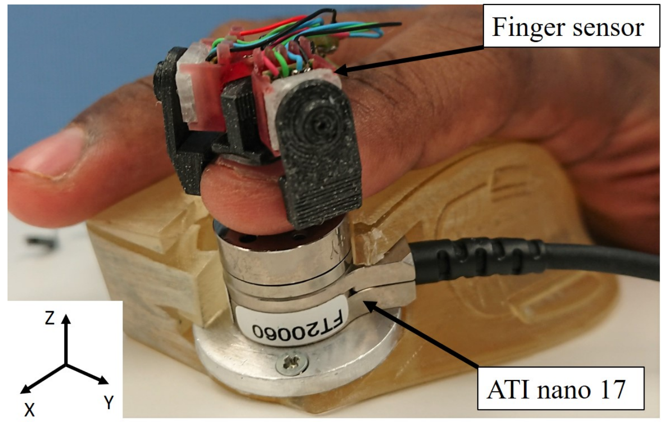


Fig. 2: Experiment Setup

The 6-axis force torque sensor was housed within an ergonomic palmrest. The palmrest was designed to rigidly mount the sensor and inherently prevent it from displacing due to the force applied by the fingertip. The shape of the palmrest was inspired by the shape of a computer mouse as shown in the Fig. 2. The palm rest facilitated to apply forces with only the finger, as well as placing each subject's finger in the same position for all trials.

B. Calibration Procedure and Experiment

The calibration and evaluation were performed with 8 subjects. Both for obtaining training and test data the subjects were asked to follow a set of instructions, which will be explained in detail in the next subsections. The identical procedure was followed for the calibration process as the one followed in [2]. The candidates were also given visual feedback via the Unity visualization software which visualizes the force vector that the wearer applies on the F/T sensor as measured by the F/T sensor in addition to displaying the forces measured by the fingertip tactile sensor (after the calibration had been performed). The load limit of the 6-axis F/T torque sensor is 15N in any direction. The subjects were asked to apply maximally 6N, which according to our experiments is the maximum force that humans can apply comfortably when using only the finger to exert force. Higher forces can be exerted for short time, and indeed in our experiments some subjects applied peak forces of up to about 9N when overshooting before achieving the target force.

In our previous paper, the subjects applied higher forces, which is possible when not only the finger, but also the hand or arm apply the force. By resting the hand on the palmrest we could limit the forces to those applied by the finger. As we want to study fine manipulation, that is a more appropriate setting. Furthermore, the results from our previous work showed that the fingerpad deformation saturates when applying higher forces [1].

For all 8 subjects we gathered data both with the previous design of the sensor [1] and the sensor described in this paper, to be able to compare the new design to the previous one.

1) Procedure to Acquire Calibration Data: In preliminary experiments we observed that a systematic way to gather calibration data provided better results than using random inputs to calculate the calibration parameters. Therefore, we used the following sequence for each subject to gather training data.

Stage 1: Preparation. The mechanism features a clamp which can be adjusted to fit fingertips of various shapes and sizes. The subjects were asked to attach the fingertip sensor, with the sensor being glued with double-sided sticky tape to the human fingernail.

They were then shown the proper way to apply the force on the sensor cap by resting their palm firmly on the palm rest and applying force by only using their fingertips while keeping also their fingers fully rested on the palm rest. As the subjects applied the force by pressing on to the F/T sensor, the 3-axis force as measured by the F/T sensor was shown on the screen of the visualization software. The measurements from the finger tactile sensor were not shown in this step. The subjects were then asked to apply some forces of their choice to get familiar with the system. In particular, the subjects were asked to apply forces as high as possible in each direction as they can with ease. The screen furthermore showed a timer, which counted from 0 to 100 seconds during the acquisition of the training data required for the calibration process.

Stage 2: Calibration protocol. After the subject said that he/she is ready we instructed him/her to initiate the calibration process by following the instructed protocol.

Step I. For the first 20 seconds, the subjects were asked to apply a constant shear force in -X direction by pressing and applying a shear force without sliding the fingertip. The force to be applied in -X direction was the maximum force that the subject in the preparation phase applied in that direction with ease. The Z axis force which was applied while pressing the F/T sensor was not specified, however a substantial force in Z axis is required to avoid sliding.

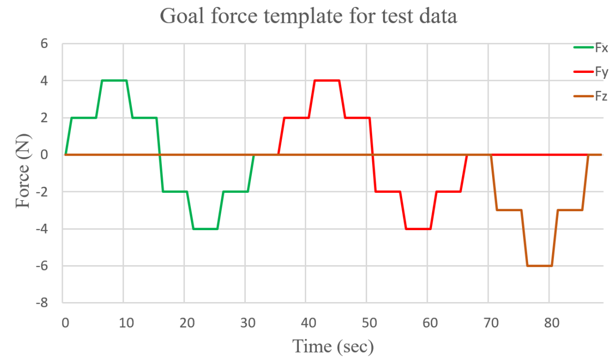


Fig. 4: The staircase shaped profile for acquiring the test data for each participant.

Step II-IV. For 20 seconds each, step I was repeated in +X, -Y and +Y direction, respectively.

Step V. From second 81 to 100, the subjects were asked to apply a constant force (the strongest force they can apply with ease) in -Z direction by only pressing down on the F/T sensor. No shear force was asked to be applied in this step.

2) Procedure to Acquire Test Data: To gather test data, the subjects were asked to apply stepwise force, in particular a sequentially increasing and then decreasing staircase shaped force profile for each force direction, as shown in Fig. 4. Even though in the graph the maximum magnitude of the goal for F_z is 6N, the maximum force that the subjects were asked to apply was only the force that they were able to apply with ease and was therefore dependent on the subject. The goal increments for the z-axis were 2N, while they were 1N for the shear forces. However, subjects found it hard to follow the goal increments especially for the z-axis, and often much higher increments than 2N were performed, to which we reacted by decreasing the number of steps if necessary. The maximum goal force for the z-axis was the maximum force applied with ease in the preparation step, and was therefore different for each subject.

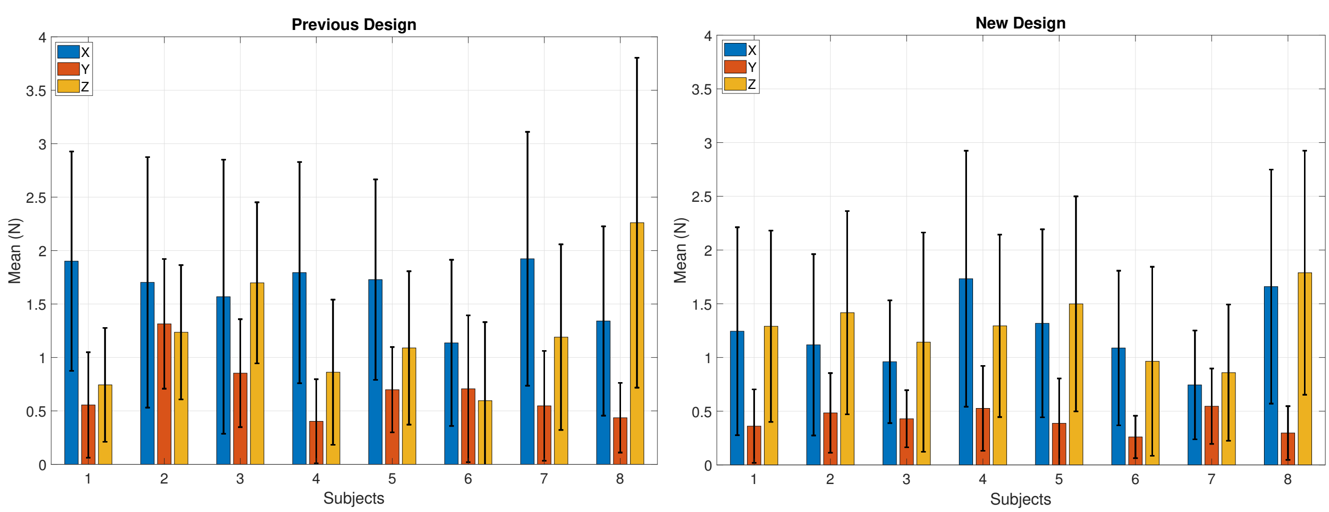
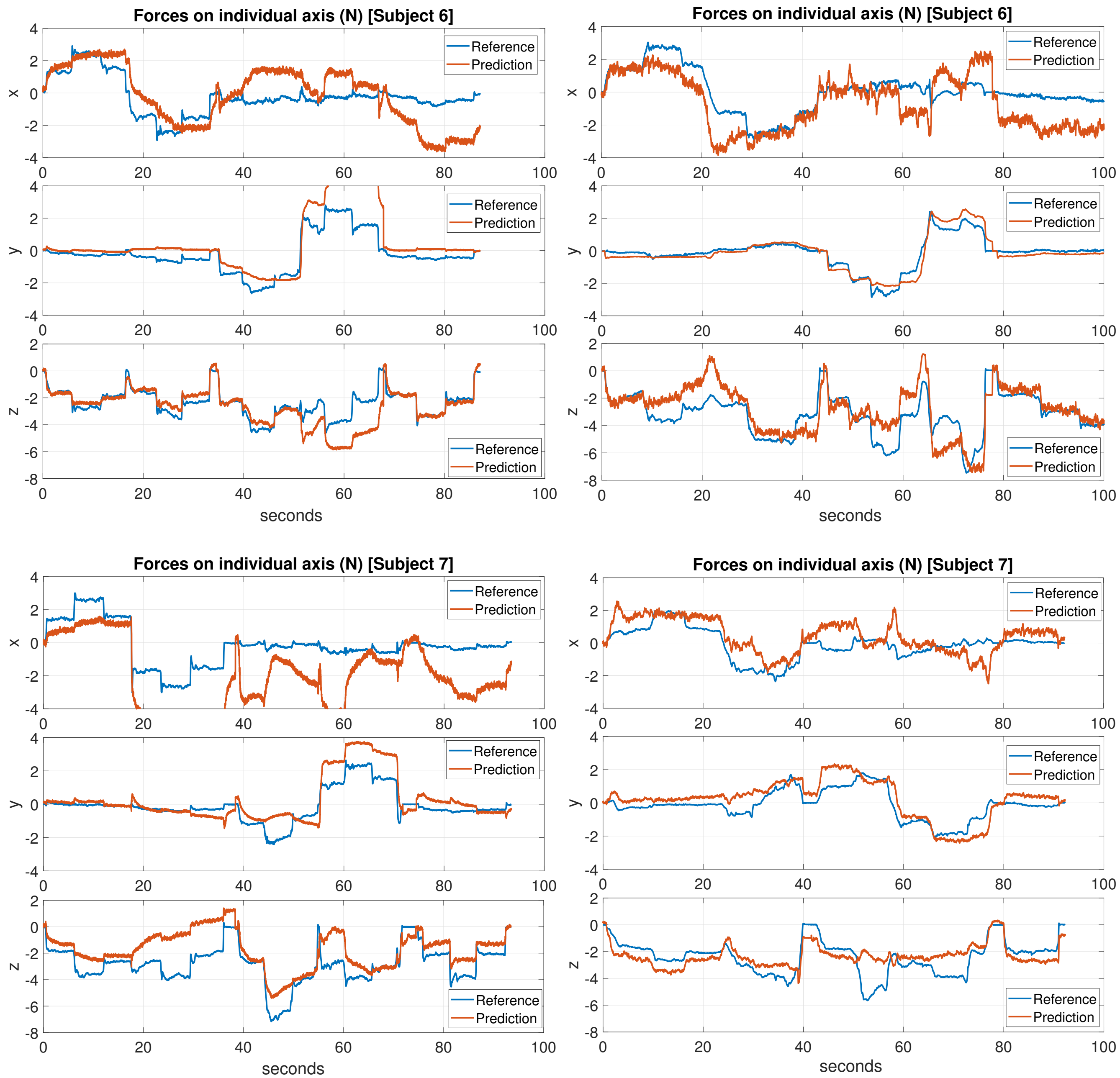


Fig. 3: Mean Absolute Error and Standard Deviation value comparison between old and new design



(a) Previous design

(b) New Design

Fig. 5: Comparison of force value prediction in time series

Regarding the shear forces, the data gathered in the calibration step indicated that the maximum shear force that could be applied was about 2 N in each direction (+X,-X,+Y,-Y) for each subject. Therefore, the forces to be applied in the shear directions were set the same for all subjects. Each force step was to be applied for about 5 seconds.

V. Results

To evaluate the newly designed finger sensor, we compare it to the previous design. Using the procedure as explained before, test data was taken for 8 people. For each subject, the mean absolute error and standard deviation were calculated for each axis and then compared with the previous design as shown on Fig. 3. The graph shows the improvement of the new design with a reduced error compared to the previous design.

A t-test was also performed to confirm the improvement between the old and new design. On each axis, a left-tailed t-test with paired sample was performed on all subject's mean absolute error on both the new and old design. With the parameter p=0.05 (95% confidence level), the t-test values are as follow; 0.0216(x-axis), 0.0167(y-axis), 0.6683(z-axis). As the t-test values of the x-axis and y-axis were less than the p value, both the x-axis and y-axis showed statistically significant improvement. On the other hand, there was no significant improvement on the z-axis.

Fig 5 shows two subjects' (subject 6 and subject 7) 3-axis force prediction in time series and the force reference from the 6-axis F/T sensor. As has been analyzed using t-test before, the new design's performance improved for the x and y axes while no significant improvement on the z axis was displayed.

In the new sensor design, the lever and the ortho-planar spring were designed such that the initial distance (without force being applied) between the permanent magnet and the Hall effect sensor was reduced to 1 mm compared to 4-7 mm in the old design. Thereby, we significantly increased the signal to noise ratio and the finger sensor's performance.

VI. CONCLUSIONS

Compared to our previous work [1], the finger sensor's performance improves due to the use of an ortho-planar spring and due to the closer distance between the permanent magnet and the Hall effect sensor. The t-test confirmed a statistically significant improvement for the x and y axes.

For future work, the structure and the material of the ortho-planar spring will be revised to achieve a better spring deformation characteristic in 3-axis and also to be sensitive enough to measure the fingerpad deformation. Four instead of two 3-axis Hall effect sensors can be used for each fingertip, similar to [2].

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