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Gait Sensing and Haptic Feedback Using an Inflatable Soft Haptic Sensor[1]

Collecting gait data and providing haptic feedback are essential for the safety and efficiency of robot-based rehabilitation. However, readily available devices that can perform both are scarce. This work presents a novel method for mutual sensing and haptic feedback, through the development of an inflatable soft haptic sensor (ISHASE). The design, modeling, and characterization of ISHASE are discussed. Four ISHASEs are embedded in the insole of a shoe to measure ground reaction forces and provide haptic feedback. Four participants were recruited to evaluate the performance of ISHASE as a sensor and haptic device. Experimental results indicate that ISHASE can accurately estimate user's ground reaction forces while walking, with a maximum and a minimum accuracy of 91% and 85%, respectively. Haptic feedback was delivered to four different locations under the foot, and users could identify the location with an average 92% accuracy. A case study that exemplifies a rehabilitation scenario is presented to demonstrate ISHASE's usefulness for mutual sensing and haptic feedback. [DOI: 10.1115/1.4064377]

Keywords: soft sensor, soft haptic device, GRF sensing, foot haptics, biomechatronics, estimation, haptics, medical robotics, pneumatics, sensors and sensor networks, service/rehabilitation robots

1 Introduction

Gait sensing and haptic feedback are essential for robot-based rehabilitation. Both rigid exoskeletons and soft exosuits have been developed to provide physical assistance during rehabilitation training [1]. Gait sensing is required to monitor user's state and to determine when to provide assistance. Commonly paired with gait sensors in gait retraining, haptic feedback is a method used to adjust and improve the gait of participants and recovering patients [2–4].

One popular approach for gait sensing is by measuring the ground reaction force (GRF) on the foot through embedded sensors in a shoe insole. Gait sensors can be categorized based on the sensing mechanism used, namely, resistive, capacitive, inductive, optical, and soft pneumatic sensors [5]. Among all these sensing mechanisms, only soft pneumatic sensors have the mechanical capability to generate force.

Soft pneumatic sensors have been used for sensing curvature [6], size of objects [7], and external forces [8]. Despite many applications of soft inflatable sensors, their use in insole sensing is limited. A previous work explored the use of coiled silicone

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tubing to measure GRF for gait sensing [9]. Fabrication of such sensors is complex and requires recalibration prior to use.

The most common form of haptic feedback is through vibration motors. These motors can relay commands through physical sensation that a user can understand, such as commands from a therapist to a patient during rehabilitation training. Studies have demonstrated that using vibration motors has important implications for the recovery of patients [2–4]. However, vibration motors are typically manufactured with rigid materials that lead to a heavy and bulky design. This is a significant limitation, as patients with neuromuscular disorders have weakened muscles and diminished volitional control [10].

Recently, a new form of haptic feedback has been introduced through soft pneumatic actuators. By using laminated bladders and a textile shell, soft pneumatic actuators were created to provide haptic feedback to participant's lower limb [11]. Like with vibration motors, participants were able to identify when the haptic feedback was provided. However, this implementation required additional hardware (footswitches and motion sensors), which increases the complexity of the system.

While studies have shown the necessity for gait sensing and haptic feedback in rehabilitation, there does not exist an integrated and adjustable wearable device that can perform both functions. Motivated by the need for such devices in neurorehabilitation, this work proposes a fabric-based inflatable soft haptic sensor (ISHASE) to measure GRFs and provide haptic feedback to the foot. Through experiments, we demonstrate that our device is capable of performing both actions: sensing the user's gait and providing haptic feedback during gait training. This is a unique feature that has significant implications in a physical rehabilitation scenario, as demonstrated through a case study.

2 Working Principle

2.1 Sensor Working Principle. The working principle of the sensors is based on the property that a change in the volume of a sealed inflated chamber causes a change in internal pressure, according to Boyle's law (1), where P is pressure and V is volume.

$$PV = \text{Constant} \quad (1)$$

Therefore, an inflated chamber exhibits a change in internal pressure when it is subjected to an external force that causes deformation and change in volume, as depicted in Fig. 1. The change in internal pressure can be used to estimate the external force exerted over the chamber.

2.2 Haptic Actuator Working Principle. The working principle of the haptic actuator is based on the capability of an inflatable actuator to generate axial force when it is compressed, such as within the insole of a shoe. Consider a deflated balloon that is compressed on both sides, as shown in Fig. 1. When the balloon is inflated at pressure P_0, the actuator generates force F. However, the actual haptic force depends on the compression forces, the distance between the compressing surfaces, and the contact area, which are highly variable in soft actuators and therefore require characterization.

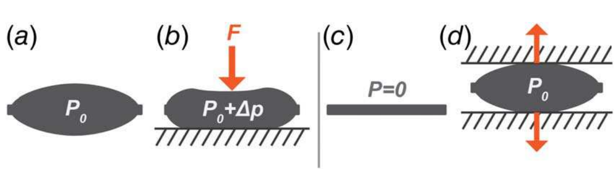

Fig. 1 ISHASE working principle. Sensing principle: a pressurized sensor at P_0 (*a*) experiences an increase in pressure to $P_0 + \Delta P$ when subjected to an external force F (*b*). Haptic principle: a deflated actuator (*c*) that is inflated to P_0 generates a force F (*d*).

Table 1 Functional requirements for GRF sensing and haptic feedback

Maximum payload	900 N
Dimensions of sensor	≤50 mm × 50 mm
Height of insole	≤15 mm
Haptic pressure intensity	<50 N/cm^2

3 Design and Fabrication

3.1 Functional Requirements. The design of the ISHASE is driven by the functional requirements for insole sensing and haptic feedback that are outlined in Table 1. The average GRF exerted by a human foot while walking is 900 N [12]. Therefore, the ISHASE is designed with the capacity to measure normal forces up to 900 N. Considering the dimensions of a standard size 9 insole, the maximum length and width of the insole ISHASE are limited to 50 mm. The maximum height of the ISHASE is constrained to match the standard height of a shoe insole, which is approximately 15 mm.

The study by Graven-Nielsen et al. [13] identified that the maximum pressure intensity before causing pain is approximately 50 N/cm^2, which sets the requirement for the haptic actuator's maximum force.

3.2 Sensor and Haptic Actuator Design. The ISHASE was developed through an iterative process. The design parameters are illustrated in Fig. 2, and the design iterations are summarized in Table 2. To start with, square ISHASE of dimensions 20 mm, 25 mm, 30 mm, and 35 mm were manufactured and inflated to an internal pressure of 240 kPa. These designs achieved a minimum height of 23 mm, which did not meet the insole height requirement. To reduce the height to less than 15 mm, the length and width were modified, following a procedure similar to the study by Nguyen et al. [14]. Through this procedure, we obtained an ISHASE design with 70 mm length and 16 mm width, which failed to satisfy the dimension requirement. To keep the same height and decrease the length, ISHASE's length was cut in half (35 mm).

To verify whether the design satisfies the range of force measurement, compression tests were performed on the ISHASE using a universal testing machine (UTM) (Instron 5944, Instron Corp., High Wycombe, UK), as shown in Fig. 3. A chamber size of 35 mm by 16 mm was used for this test. Different ISHASE configurations were tested with a single chamber, double chambers, and

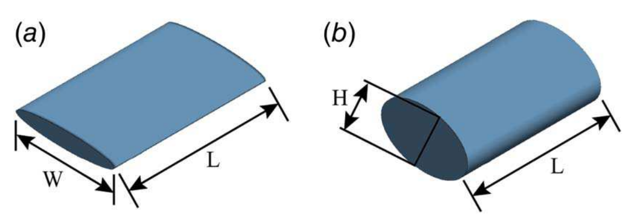

Fig. 2 Design parameters. (*a*) Deflated ISHASE with width *W* and length *L*. (*b*) Inflated ISHASE reaches height *H*.

Table 2 Design iterations

W (mm)	L (mm)	H (mm)	Chambers	F_{max} (N)
20	20	≥23[a]	1	≤450[a]
25	25	≥23[a]	1	≤450[a]
30	30	≥23[a]	1	≤450[a]
35	35	≥23[a]	1	≤450[a]
16	70[a]	12	1	200[a]
16	35	12	2	600[a]
16	35	12	3	1000

[a]Functional requirement is not satisfied.

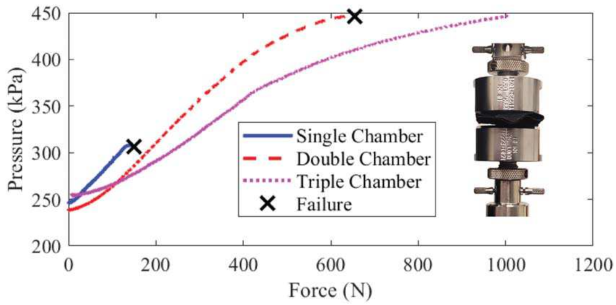

Fig. 3 Force testing for multiple chambers. The picture shows the ISHASE between the UTM compression plates.

triple chambers, as summarized in Table 2. The compression test results, shown in Fig. 3, reveal that the single and double chamber designs fail at approximately 200 N and 600 N loads, respectively. The triple chamber is the only configuration that demonstrated the capacity to withstand forces up to 900 N, which satisfies the functional requirements.

3.3 Fabrication. The fabrication methodology adopted for the ISHASE is as follows. First, the dimensions of each chamber are drawn on two thermoplastic polyurethane (TPU) layers. An orifice is created to insert a plastic tube for airflow and pressure measurement. The tube is glued from both sides to create a leak-proof seal. The sides of the TPU layers are then heat sealed to create a hollow inflatable chamber. Finally, the TPU chamber is placed inside a nylon fabric pocket, made by sewing together two layers of nylon fabric. Adding the reinforcement nylon fabric increases the structural stiffness, which allows the ISHASE to sustain high pressures. The fabrication process is similar to the methodology in Ref. [15].

The final ISHASE design is presented in Fig. 4. This design consists of three 16 mm-by-35 mm chambers that are sewn parallel to one another. The overall dimension of the ISHASE is 48 mm by 35 mm and achieves a height of 12 mm when inflated. A four-way barbed connector is used to connect all three chambers to a pressure sensor and to a compressed air source for inflation. To create a leak-proof sensor, a one-way valve was connected.

3.4 Shoe and Insole Design. The shoe design, presented in Fig. 5(*a*), contains the ISHASE that measures GRFs. Four ISHASE were placed under the insole of the shoe and positioned at the heel, toe, between the first and second *metatarsophalangeal* joint (Meta12), and between the fourth and fifth *metatarsophalangeal* joint (Meta45), as depicted in Fig. 5(*b*). With this shoe

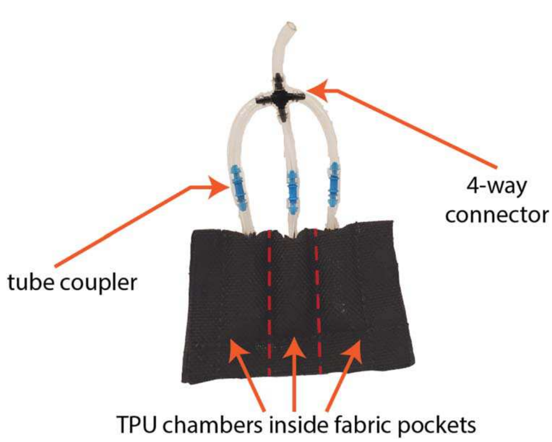

Fig. 4 ISHASE design overview. The dashed lines depict the stitch line that separates the three chambers.

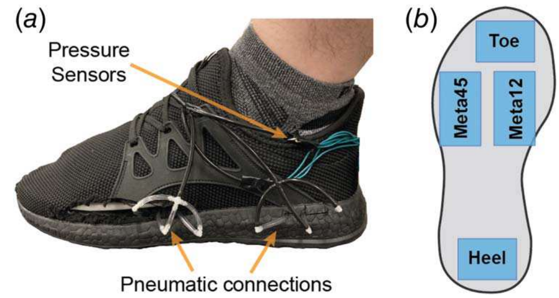

Fig. 5 (*a*) Shoe with embedded inflatable sensors–actuators and (*b*) sensor placement on the insole

design, the total GRF can be estimated by adding the readings of the four insole sensors. The ISHASE was packed between two thin acrylic sheets to minimize the effect of the unmodeled shear forces and the losses due to partial contact with the shoe (instead of the insoles). Holes were cut on the sides of the shoe for the sensor's tubing connections. An air compressor provides the pressure source to inflate the ISHASE. Pressure sensors (ABP-DANN100PGAA5, Honeywell International Inc., Charlotte, NC) were connected to measure the ISHASE's internal pressure. Solenoid valves (MHE3-MS1H valves, Festo, Eatontown, NJ) were used to operate the inflation and deflation process. A microcontroller (Ar-duino Uno, Arduino) was used to record the sensor data and to control the haptic actuators. The microcontroller and electropneumatics were placed in an off-board unit that weighs less than 3 kg and measures $10 \times 10 \times 5$ cm. As a result, the majority of the system is designed to be wearable. However, due to the air compressors, the experiments are currently limited to a treadmill environment.

4 Modeling and Characterization

4.1 Sensor Modeling and Characterization. The sensor model, which maps the relationship between external forces and internal pressure, was built through experimental characterization. This model allows estimation of external forces by measuring the internal pressure. Dynamic characterization of the ISHASE's was performed through compression tests using a UTM. The ISHASE was pre-inflated to 200 kPa and then compressed in the UTM for 12 consecutive cycles while collecting data on the applied force and the internal pressure change. A pressure sensor was connected to the ISHASE to measure the internal pressure. Different loading rates were implemented in the UTM as it relates to variations in walking speed.

The force–pressure curve in Fig. 6 reveals a proportional relationship with some linear trend. Variations in speed did not have a significant effect on the characterization curve; therefore, only the 150 mm/min data was used to build the model. A linear model (2) and an exponential model (3) were fitted (linear: $R^2 = 0.976$, root-mean-square error (RMSE) = 28.4 N; exponential: $R^2 = 0.988$, RMSE = 19.75 N) between the applied force F and the internal pressure P. In these controlled experimental conditions, the exponential model (3) demonstrated better-fit performance.

$$F = 2.688P - 448.3 \tag{2}$$

$$F = 39.7e^{(0.007P)} - 8686e^{(-0.0253P)} \tag{3}$$

An additional data set was collected at 150 mm/min for model validation. The validation for the linear model (2) and the exponential model (3) yielded an RMSE of 35.3 N and 22.8 N, respectively, which corresponds to a maximum 3.9% error of the full-scale range (900 N). Hysteresis between loading and unloading can be observed in Fig. 6, which could contribute to modeling errors.

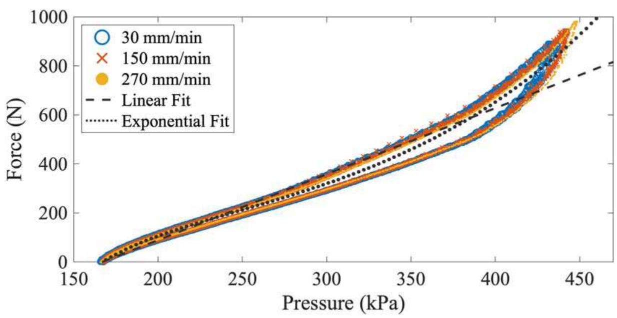

Fig. 6 Sensor modeling and characterization.

4.2 Sensor Repeatability. Repeatability demonstrates the capability of a sensor to maintain robustness through multiple cycles. The standard deviation of the ISHASE's force estimate will be used as the metric for repeatability. Cyclic compression of the ISHASE was performed in a UTM for 40 cycles while collecting force data. Different loading rates were implemented in the UTM as it relates to variations in walking speed. The peak force for each cycle was recorded, and its standard deviation was computed, yielding 5.2 N, 2.8 N, and 3.2 N for loading rates of 30 mm/min, 150 mm/min, and 270 mm/min, respectively. Considering the ISHASE's full-scale measurement range (900 N), the standard deviation results imply that for the worst case (5.2 N) the ISHASE is repeatable within 99.4% of the sensor full-scale range. The results demonstrate that the ISHASE has exceptional repeatability that is robust to different speeds.

4.3 Haptic Actuator Characterization. The force output of the haptic actuator was characterized to quantify the amount of force delivered to the human and to verify that it is within a safe range that does not cause pain. The ISHASE was placed in a UTM between two compression plates, similar to the picture in Fig. 3. Different preload conditions were tested to represent the compression forces of the user's foot over the ISHASE, while it provides haptic feedback. Preload conditions of 250 N, 350 N, and 450 N were tested, which correspond to subjects that weigh 500 N, 700 N, and 900 N, respectively. The ISHASE was inflated at different pressures, and the haptic force generated was recorded. Approximately 40 force samples were collected for each preload and pressure condition.

The average force data for each pressure and preload condition are shown in Fig. 7. The results corroborate that at the maximum pressure tested (150 kPa), the ISHASE generates sufficient force to be detected (110 N) and delivers a pressure intensity of 6.5 N/cm^2, which is below the pain threshold. In addition, the results reveal that an increase in the preload compression leads to a reduction in the delivered haptic force. This implies that for heavier subjects the delivered haptic force is diminished. However, the ISHASE exhibits the capability of providing sufficient force feedback to be detected by even the heaviest user tested (900 N).

5 Evaluation With Human Subjects

The ISHASE was tested with human participants to evaluate the capability for gait sensing and providing haptic feedback to a user. Four healthy participants (74.9 ± 16.1 kg, 1.73 ± 0.15 m, 26 ± 3.9 years, three males and one female) were recruited. The experimental protocol was approved by the Arizona State University Institutional Review Board (IRB ID: STUDY00011110).

5.1 Sensor Evaluation for Gait Sensing. The goal of this experiment is to use the ISHASE to estimate the total GRF of a human while walking. Each participant wore the ISHASE-embedded shoe, shown in Fig. 5, while walking on an instrumented split-belt treadmill (Bertec Inc., Columbus, OH) equipped with two force plates that measure the GRF at 1000 Hz, which were used as ground truth. The participants walked for approximately 100 steps at a speed of 0.5 m/s and 0.75 m/s. The GRF data for each walking trial were segmented into individual gait cycles. The 100 segmented gait cycles were temporally normalized to gait cycle percent to compute the GRF average and standard deviation through the walking cycle.

The GRF average and standard deviation for one participant while walking are shown in Fig. 8. The ISHASE's RMSEs of the GRF estimation are presented in Table 3. The results demonstrate that ISHASE can accurately estimate GRF with a maximum of 91% accuracy (70.99 N RMSE corresponds to 9% of Subject 4's body weight) and a minimum of 85% accuracy (74.28 N RMSE corresponds to 15% of Subject 3's body weight). A possible source of error could be due to friction of the foot on the inner sides of the shoe, which suggests that not all forces are transmitted to the insole; this effect is most noticeable during the stance phase (0–60% gait cycle). In the swing phase, the error is because when the shoe is worn there is compression pressure due to the tightening of the shoe laces, which is not accounted for in the individual sensor model.

The human subject experiments revealed that the linear model (2) achieves better estimation performance than the exponential model (3). Exponential fits can be highly sensitive to outliers in the data. In the subject experiments, there is a significant presence of unknown disturbances, such as shoe friction and compression forces, which introduce outliers. As such, the exponential model tends to amplify errors related to unknown disturbances that surfaced during the subject experiments. Finally, the exponential model could be overfitting the undisturbed and noise-free data (Fig. 6), and as a result, it might not perform well for data with unknown disturbances and noise. In contrast, the linear model is simpler and makes fewer assumptions and therefore can be more robust to variations caused by unknown disturbances and noise.

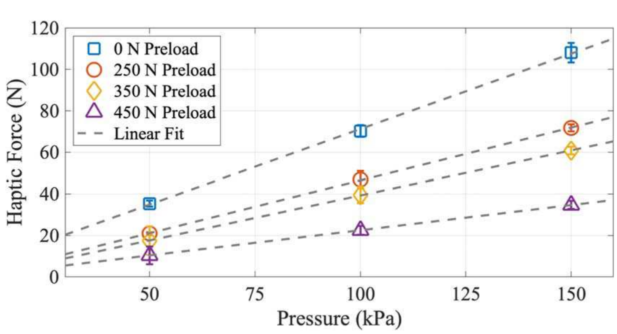

Fig. 7 Haptic force characterization. For each case, the average and standard deviation of 40 samples are shown.

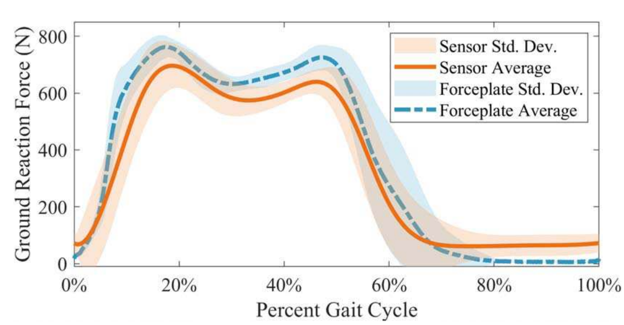

Fig. 8 GRF of the human participant while walking. The sensor GRF was obtained with the linear model (2).

Table 3 RMSE of GRF estimation at different walking speeds

		Linear model (2)		Exponent model (3)	
Subject	Weight	0.5 m/s	0.75 m/s	0.5 m/s	0.75 m/s
1	82.5 kg	94.9 N	100.9 N	135.5 N	114.8 N
2	88.1 kg	93.3 N	100.8 N	122.3 N	96.66 N
3	51.7 kg	64.9 N	74.28 N	71.60 N	107.7 N
4	77.3 kg	90.4 N	70.99 N	89.43 N	89.37 N

Table 4 Success rate of haptic feedback identification for subject 4

	100 kPa	50 kPa
10 Hz	98%	92%
100 Hz	96%	82%

5.2 Haptic Feedback Evaluation. The goal of this experiment is to demonstrate that the human user can identify the sensation of the haptic feedback from ISHASE. Each participant wore, on the left foot only, the ISHASE-embedded shoe in Fig. 5(*a*), and was asked to identify where the haptic feedback was delivered under the foot. To provide haptic feedback, the ISHASE was inflated and deflated rapidly at a fixed frequency to induce a vibratory sensation. Different frequencies (10 Hz and 100 Hz) and different inflation pressures (50 kPa and 100 kPa) were tested. Each trial consisted of 50 rounds of feedback at randomized locations, and each round lasted for 0.5 s.

The haptic results presented correspond to a representative subject (Subject 4). The overall success rates for different frequencies and inflation pressures are summarized in Table 4. The confusion matrix of the lowest performing trial (100 Hz, 50 kPa) is shown in Fig. 9. The results demonstrate that the user is capable of sensing the haptic feedback and even identifying its location. The results revealed that low frequencies contribute to an improvement in haptic feedback identification. One possible reason is that, at a lower frequency, the actuator can fully inflate and provide high force. Higher pressures also improved the haptic feedback identification, due to a similar reason.

5.3 Case Study for Sensing With Haptic Feedback. In this work, we present a case study that demonstrates the use of the ISHASE's dual capability for sensing and providing haptic feedback in a rehabilitation task. A common rehabilitation scenario involves a human performing physical activity while a therapist monitors and gives commands. In our case, the physical activity is sit-to-stand transition, and all commands from the therapist to the user will be provided through the shoes as shown in Fig. 5(*a*). As such, this experiment focuses on using the ISHASE to simultaneously estimate the human states and provide haptic feedback to guide the user.

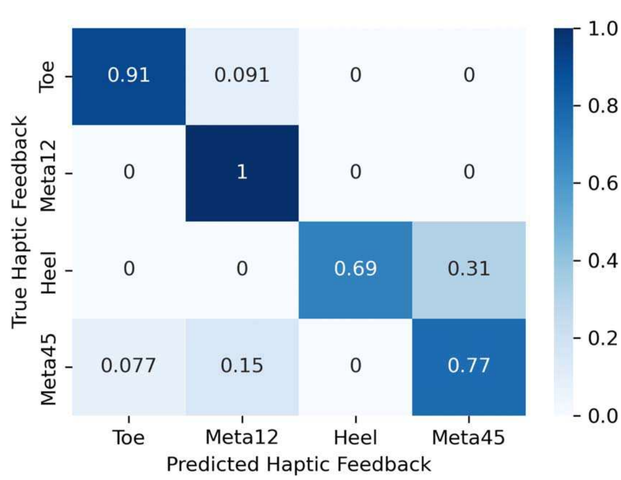

Fig. 9 Confusion matrix of haptic feedback identification for trial with lowest performance (100 Hz and 50 kPa).

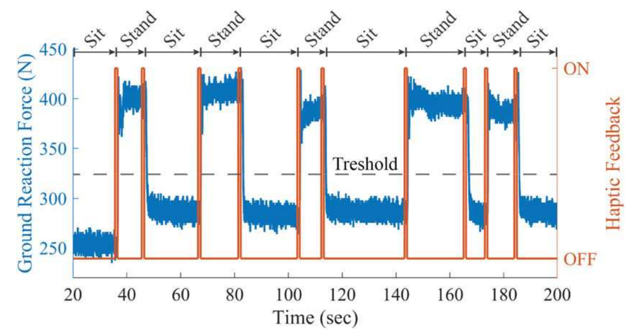

Fig. 10 Sensor GRF measurements and haptic actuation signal through the case study experiment.

The participants were guided to transition between sitting down and standing up when they felt the haptic feedback. The transitions between sitting down and standing up are monitored with the ISHASE's GRF measurements. The transitions to standing up are detected when the GRF measurement exceeds a threshold that is determined before the start of the experiment (GRF > 325 N for subject 1). Once a transition is detected, a randomized delay is introduced before the next haptic feedback (indication) is provided. The experiment had a duration of 7 min.

Figure 10 shows ISHASE's sensor and actuation signals for a representative subject (subject 1). This plot shows that the ISHASE-embedded shoe is capable of accurately detecting transitions between sitting down and standing up. In addition, the results show that every time haptic feedback is delivered, the user immediately captures and reacts to it. This serves as preliminary evidence that the therapist can send commands, through the shoe, to modify or engage in the physical activity of the patient. This could allow the therapist to focus on adjusting gait or training parameters during rehabilitation since the developed ISHASE takes care of the real-time monitoring and signaling to the user.

6 Conclusion

This work introduced a soft inflatable device to perform mutual gait sensing and haptic feedback. The development of the ISHASE addressed a gap in the availability of devices that can perform both actions. The ISHASE's design, fabrication, modeling, and mechanical characterization were discussed in detail. Four ISHASEs were embedded into a shoe insole to monitor gait and provide haptic feedback to user's foot. The sensor model was developed with experimental data and achieves an accuracy of 35.3 N (3.9% error of the sensor's full-scale range). In practical applications, the ISHASE demonstrated the capacity to accurately estimate the GRF of a user while walking, with a maximum and minimum accuracy of 91% and 85% respectively. The ISHASE was also evaluated as a haptic device, and the results reveal that the users can identify the haptic feedback location. Furthermore, the application of the ISHASE as a mutual gait sensor and a haptic actuator was explored through a case study that exemplifies a physical rehabilitation scenario. The case study demonstrated that the ISHASE can be used to autonomously monitor the state of the human while simultaneously also used to provide indications to the user through haptic feedback.

Future work will include improving the design to ensure robustness for extended use. The sensor model will be improved to account for compression forces within the shoe and forces that are lost due to friction with the shoe. Furthermore, we aim to perform mutual sensing and haptic feedback by developing a dynamic estimation model that robustly estimates external forces in the presence of dynamic pressurization.

Funding Data

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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