Mitigating Thermal Expansion Effects in Silicone-Coated Pelvic Floor Muscle Dynamometer

Nikolay Papanchev
Robotics Engineering Department
Université de Sherbrooke
Sherbrooke, Canada
Nikolay.Papanchev@usherbrooke.ca

Simon Richard
Mechanical Engineering Department
Université de Sherbrooke
Sherbrooke, Canada
Simon.Richard@USherbrooke.ca

Leonard Oest O'Leary
Computer Science Department
Université de Montréal
Montréal, Canada
leonard.oest.oleary@umontreal.ca

Marc Feeley
Computer Science Department
Université de Montréal
Montréal, Canada
feeley@iro.umontreal.ca

Chantale Dumoulin
School of Rehabilitation
Université de Montréal, and Institut Universtaire de Gériatrie de Montréal
Montréal, Canada
chantal.dumoulin@umontreal.ca

Cederick Landry
Mechanical Engineering Department
Université de Sherbrooke, and Research Center on Aging
Sherbrooke, Canada
cederick.landry@usherbrooke.ca

***Abstract*— Objective: Various types of sensors, such as dynamometers, have been developed to assist in strengthening the pelvic floor muscles, aiming to improve the quality of life for women affected by urinary incontinence. This paper presents silicone encapsulation method for portable vaginal dynamometers that minimizes force measurement drift caused by thermal expansion mismatch between the silicone and the dynamometer housing due to body temperature. Methods: The encapsulation process involves two steps. First, based on the size and shape of the dynamometer, a mold is created to form a cured silicone sleeve slightly larger than the sensor. This sleeve is then slid over the dynamometer. A second silicone layer is subsequently applied over the sleeve and any exposed surfaces of the dynamometer. The dynamometers were tested in air and water at 40 °C to simulate thermal conditions and assess the force measurement drift at body temperature. Results: The proposed method limited the force drift to 0.014 N—a significant reduction compared to the 5 N observed when the silicone was directly applied to the dynamometer surface. This demonstrates the effectiveness of the two-layer encapsulation in mitigating the impact of thermal expansion on the measured force. Significance: This may pave the way to accurate personal pelvic dynamometers for at-home and personalized pelvic muscle training.**

I. Introduction

Urinary incontinence is a prevalent condition that significantly affects the quality of life of millions of women worldwide [1]. Characterized by the involuntary leakage of urine, urinary incontinence can lead to both physical discomfort and psychological distress [2]. One of the primary contributors to urinary incontinence is the weakening of the pelvic floor muscles (PFM), which play a critical role in maintaining continence by supporting the bladder and urethra [3].

Assessing the strength of the PFM is therefore essential for both diagnosis and treatment planning. Among the available assessment tools, dynamometry offers a reliable and quantitative method for measuring muscle force [4].

This work was supported in part by CIHR Project Grant (504871) and INTER (153B).

Corresponding author: cederick.landry@usherbrooke.ca.

Recently, wireless, wearable dynamometer systems have been introduced to provide feedback during pelvic exercise prescribed in rehabilitation programs [5]. However, great variability in these systems design is observed in the literature with no guarantee in the validity of the absolute force measurement accuracy [6].

Building on the foundational work presented in El-Sayegh *et al*. [7], this work focuses on the design and implementation of a silicone encapsulation method that enhances force measurement stability at body temperature (37 °C) by reducing thermally induced undesired stress. Like most, if not all, systems, the dynamometer presented herein must be calibrated at room temperature [7], yet remain accurate when operating at body temperature.

The main contribution of this works lies in the development of a two-step silicone encapsulation method that minimizes the effect of thermal expansion mismatch between the silicone and the dynamometer housing on the dynamometer force measurements.

Figure 1: Encapsulated dynamometer

II. SENSOR DEVELOPMENT

Figure 1 presents a picture of the silicone encapsulated dynamometer wired to its electronics. A load cell is mounted at the core of the dynamometer on two independent housing shells, enabling the measurement of applied force on the dynamometer, see Figure 2. This load cell is connected to the printed circuit board (PCB), located centrally within the device. This internal PCB is wired to a second PCB inside a casing worn at the user's belt, see Figure 2. The external PCB enables Bluetooth communication to remotely access real-time data with a user interface.

The housings for both the dynamometer and the external PCB enclosures are fabricated using 3D printing with polylactic acid (PLA) plastic.

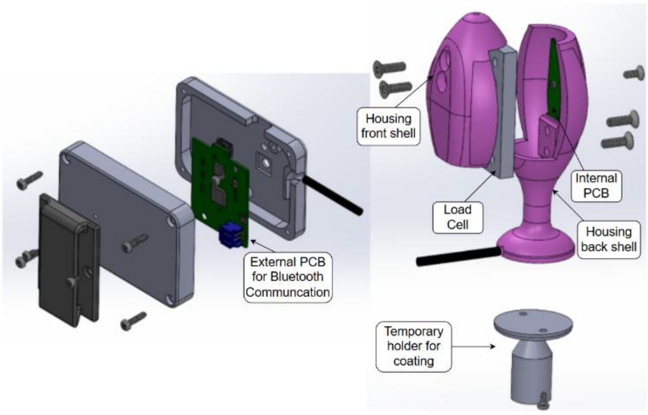

Figure 2: Exploded view of the dynamometer and its electronics

Applying a silicone coating to the dynamometer is essential to ensure proper sealing of the internal electronics and to allow proper cleaning of the device. Additionally, the dynamometer encapsulating material must comply with medical-grade biocompatibility standards to ensure safe internal use.

One of the primary challenges in integrating the silicone coating lies in managing the thermal expansion mismatch between the PLA structure and the silicone when submitted to body temperature. This mismatch must be addressed carefully to avoid introducing mechanical stress on the load cell, which could compromise force measurement accuracy. Specifically, it must perform consistently at room temperature (where the device is calibrated) and in aqueous environments at body temperature. Addressing these thermal effects is therefore essential for reliable performance and accuracy.

III. MATERIALS AND METHODS

Two encapsulation techniques were explored for coating the dynamometer with medical-grade silicone. Both designs have been tested in similar controlled environments to assess the force measurement drift.

A. Baseline Design

In the Baseline Design, the gap between the housing front and back shells was sealed with medical tape. Then, silicone was injected directly onto the sensor using a syringe and a 3D-printed mold, ensuring full coverage of the dynamometer. While this method effectively sealed the dynamometer, the silicone adhered directly to the housing. Therefore, the thermal expansion mismatch between the silicone and the housing will induce undesired forces on the device assembly, measured by the load cell.

B. Slide-Fit Design

This method involved forming a thin sleeve of silicone on a core replicating the shape of the dynamometer housing. Once fully cured, this sleeve was removed from the core and slid over the sensor, avoiding direct adhesion of the silicone to sensitive regions of the housing.
To achieve the desired shape and complete encapsulation of the dynamometer, a second layer of silicone was then applied. In this last step, the sensor was placed into a custom 3D-printed mold designed to match the full geometry of the device. Silicone was then applied uniformly along the inner surfaces of the mold before it was closed around the sensor to form the final encapsulation. The curing time of the Factor II A-103 silicone was 18h-24h. While the process was accelerated by applying heat, it was critical not to exceed 40 °C, as higher temperatures may cause deformation of both the mold and the sensor housing [8].

The Slide-Fit Design prevents silicone from adhering to both parts of the housing, thereby significantly enhancing force measurement stability by reducing thermally induced stress. As illustrated in Figure 3, the first layer covers only areas of the housing that influence the load cell's measurements, which minimizes the impact of thermal expansion on force measurements.

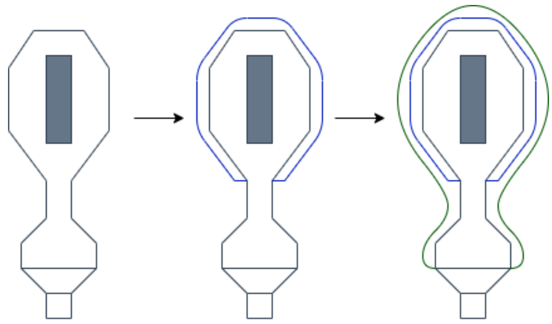

Figure 3: Schematic evolution of the silicone layers: a thin cured silicon layer is installed with no adhesion to housing (middle schematic). The entire assembly is covered with final silicone layer (right schematic)

C. Experiments

The PCB housed within the external enclosure equipped with an ESP32 microcontroller programmed with custom firmware [9] was used to enable Bluetooth connectivity and provide an interface for real-time visualization of the force measurements from the load cell. Additionally, the system was used to export the recorded data to a CSV file for further analysis.

A series of experiments were conducted to evaluate differences between coated and uncoated sensors under various environmental conditions. These tests were designed to assess the impact of silicone encapsulation on measurement accuracy, thermal stability, and waterproofing. Before each experiment, the sensor is calibrated at room temperature with calibrated masses to ensure a good reading of the values [9] and zeroed.

1) Experiment 1: Thermal Expansion in Air

In a first experiment, a dynamometer without silicone encapsulation (uncoated) was tested to assess any thermally induced drift unrelated to the silicone layer. Both Baseline Design and uncoated dynamometer were calibrated at room temperature and placed in an environmental chamber maintained at 40 °C for 30 min. A 200g mass was applied to each sensor to determine whether the force measurements recorded by the load cell accurately matched the weight of the applied mass. This setup enabled a comparative analysis of any deviations, isolating the effects of silicone-induced thermal expansion.

2) Experiment 2: Transient Response in Water

To simulate a more representative rapid thermal transition, a second experiment was conducted in a warm liquid environment for 30 min, reflecting the typical duration of a pelvic floor exercise session. The sensor was calibrated at room temperature and then submerged in a beaker filled with water heated to 40 °C using a hot plate. The temperature was monitored with a thermocouple. During the experiment, the dynamometer was supported by its base with a stable support fixture. A schematic of this setup is shown in Figure4.

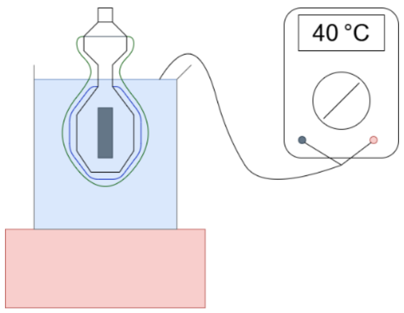

Figure 4: Schematic representation of in water experiments

IV. Results

.

A. Experiment 1 results : Thermal Expansion in air

Figure 5 shows the force readings for both, the uncoated and silicone coated dynamometers, in the environmental chamber maintained at 40 °C for 30 min under a constant load of 200g (1.96 N). The measurements showed a drift of approximately 0.005 N and -5 N, respectively.

A significant decrease in the measured force values was observed during the experiment for the Baseline Design, highlighting the substantial impact of silicone's thermal expansion on sensor accuracy.

B. Experiment 2 results : Transient Response in Water

Force readings of the silicone encapsulated dynamometers, using the Baseline Design and the Slide-Fit Design, are shown in Figure 6. The two-step encapsulation method showed minimal signal drift of 0.014 N when submerged in 40 °C water, whereas the Baseline Design showed an 8 N drift. Both dynamometers remained fully operational post-submersion, confirming the waterproof integrity provided by silicone encapsulation.

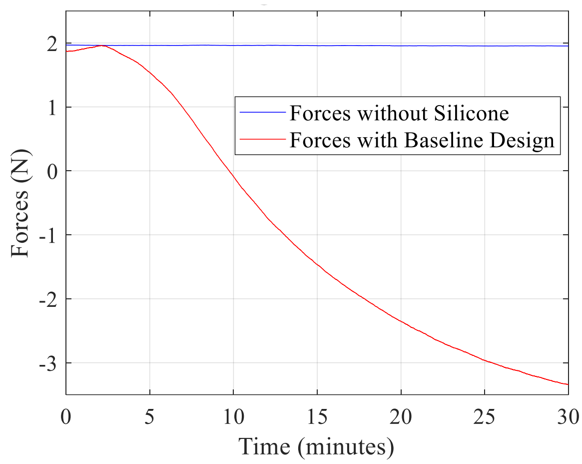

Figure 5: Dynamometer force measurements over time for a load of 200g static weight comparing the Baseline Design and the dynamometer without silicone in the environmental chamber at 40°C

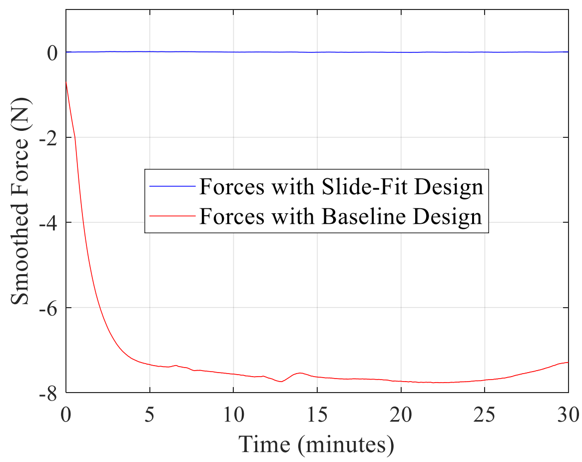

Figure 6: Dynamometer force measurements over time without load comparing the Baseline Design and the Slide-Fit Design submerged in water at 40°C

V. Discussion

This study presented a new silicone encapsulation method for portable vaginal dynamometers to enable thermally stable force measurement of PFM contractions while ensuring user safety. To our knowledge, this is the first demonstration of thermal stability for silicone coated pelvic muscle dynamometer. Our developed coating method may guide future dynamometer design to ensure precise and reliable force measurement to support rehabilitation of women with urinary incontinence. These devices have the potential to provide meaningful, real-time feedback during pelvic floor training and therapeutic exercises for improved outcomes [10].

Although medical-grade silicone is essential for encapsulating personal vaginal dynamometer to ensure biocompatibility and user protection, its thermal expansion at body temperature must be carefully managed to minimize force measurement drift after room temperature calibration. Experimental results demonstrated that directly molding silicone onto the sensor surface causes the material to adhere to the housing, resulting in a significant and undesirable drift of 5 to 8 N in the force measurements over 30 min — a typical training period (Figure 5 and Figure 6). The proposed two-step encapsulation method yielded promising results, though further validation with additional dynamometer units is necessary. Nonetheless, our Slide-Fit Design prototype demonstrated its ability to decouple the expansion of silicone from the sensor's sensitive regions. This resulted in an abysmal drift of 0.01 N in water at 40 °C over a period of 30 min. For context, previous studies have reported median PFM strength ranging from 3.6 to 5.05 N [11] on a fixed-based PFM dynamometer, although women affected by urinary incontinence may exhibit lower force values depending on the dynamometer design [12]; in-house testing with our non fixed-based PFM dynamometer has yielded pelvic muscle forces as low as 1N. Our method could reduce thermal expansion-induced drift to below 1% of typical force measurements, underscoring its potential for measuring PFM force more accurately both in assessment and intervention. Further testing in vivo and vitro and needed to confirm reliability and validity of these measurement.

Additionally, the dynamometer proved to be fully waterproof, with internal electronics remaining functional after submersion, confirming the effectiveness of the sealing technique.

The main limitation of this study is that repeatability of the coating method has not been tested. This is kept for a future study. Moreover, acknowledging the importance of validating the new coating method in real-world applications, evaluating the usability and performance of the dynamometers in a clinical study with women affected by urinary incontinence will be the next step.

VI. Conclusion

This paper presented a reliable silicone encapsulation technique for portable vaginal dynamometers designed for therapeutic training of women with urinary incontinence. The proposed two-step silicone encapsulation method ensures user safety, force measurement precision by minimizing thermal expansion-induced drift and waterproof integrity. With successful ensuing research, accurate personal vaginal dynamometers may uniquely help women with urinary incontinence with at-home and personalized pelvic muscle training.

References

[1] C. Shaw, J. Cahill, et A. Wagg, « The current state of continence in Canada: a population representative epidemiological survey », *Can J Urol*, vol. 27, nº 4, p. 10300-10305, août 2020.

[2] S. Hunskaar et A. Vinsnes, « The quality of life in women with urinary incontinence as measured by the sickness impact profile », *J Am Geriatr Soc*, vol. 39, nº 4, p. 378-382, avr. 1991, doi: 10.1111/j.1532-5415.1991.tb02903.x.

[3] B. T. Haylen *et al.*, « An International Urogynecological Association (IUGA) / International Continence Society (ICS) joint report on the terminology for female pelvic organ prolapse (POP) », *Int Urogynecol J*, vol. 27, nº 2, p. 165-194, févr. 2016, doi: 10.1007/s00192-015-2932-1.

[4] B. El-Sayegh, L. P. Cacciari, F. L. Primeau, M. Sawan, et C. Dumoulin, « The state of pelvic floor muscle dynamometry: A scoping review », *Neurourology and Urodynamics*, vol. 42, nº 2, p. 478-499, 2023, doi: 10.1002/nau.25101.

[5] N. Förstl, I. Adler, F. Süß, et S. Dendorfer, « Technologies for Evaluation of Pelvic Floor Functionality: A Systematic Review », *Sensors*, vol. 24, nº 12, Art. nº 12, janv. 2024, doi: 10.3390/s24124001.

[6] B. El-Sayegh, L. P. Cacciari, F. L. Primeau, M. Sawan, et C. Dumoulin, « The state of pelvic floor muscle dynamometry: A scoping review », *Neurourology and Urodynamics*, vol. 42, nº 2, p. 478-499, 2023, doi: 10.1002/nau.25101.

[7] B. El-Sayegh *et al.*, « Portable Dynamometer-Based Measurement of Pelvic Floor Muscle Force », *IEEE Journal of Translational Engineering in Health and Medicine*, vol. 11, p. 44-53, 2023, doi: 10.1109/JTEHM.2022.3223258.

[8] J. Luo, Q. Luo, G. Zhang, Q. Li, et G. Sun, « On strain rate and temperature dependent mechanical properties and constitutive models for additively manufactured polylactic acid (PLA) materials », *Thin-Walled Structures*, vol. 179, p. 109624, oct. 2022, doi: 10.1016/j.tws.2022.109624.

[9] B. El-Sayegh, C. Dumoulin, M. Ali, H. Assaf, et M. Sawan, « A Dynamometer-based Wireless Pelvic Floor Muscle Force Monitoring », in *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, juill. 2020, p. 6127-6130. doi: 10.1109/EMBC44109.2020.9176660.

[10] « Feedback or biofeedback to augment pelvic floor muscle training for urinary incontinence in women - Herderschee, R - 2011 | Cochrane Library ». Consulté le: 3 juin 2025. [En ligne]. Disponible sur: https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD009252/full/ro

[11] W. Moss *et al.*, « The association between pelvic floor muscle force and general strength and fitness in postpartum women », *Female Pelvic Med Reconstr Surg*, vol. 26, nº 6, p. 351-357, juin 2020. Consulté le 6 juin 2025 [En ligne]. Disponible sur: https://pubmed.ncbi.nlm.nih.gov/30921083/

[12] M. Verelst et G. Leivseth, « Force and stiffness of the pelvic floor as function of muscle length: A comparison between women with and without stress urinary incontinence », *Neurourology and Urodynamics*, vol. 26, nº 6, p. 852-857, 2007, doi: 10.1002/nau.20415.