Translating Fecobionics Into a Technique That Addresses Clinical Needs for Objective Perineal Descent Measurements

Z. Zhuang, MEng¹, H.Y. Hung, MD, PhD², S.C. Chen, MD¹, K. Futaba, MD, PhD¹ and H. Gregersen, MD, PhD¹

INTRODUCTION: Perineal descent is a phenomenon associated with anorectal dysfunction. It is diagnosed by defecography but subjected to manual measurements on the images/videos and interobserver bias. Fecobionics is a simulated feces for assessing important physiological parameters during defecation. Here, we translate Fecobionics into a new method for estimation of perineal descent based on electronic signals from the embedded inertial measurement units (IMUs).

METHODS: A displacement measurement method by a combined zero-velocity update and gravity compensation algorithm from IMUs was developed. The method was verified in a robot model, which mimicked perineal descent motion.

RESULTS: The method correlated well with the reference \( R^2 = 0.9789 \) and had a deviation from the peak displacement (range 0.25–2.5 cm) of \( -0.04 \pm 0.498 \) cm. The method was further validated in 5 human experiments with comparison to the benchmark defecography technology \( R^2 = 0.79 \).

DISCUSSION: The proposed technology is objective, i.e., electronic measurements rather than by fluoroscopy or MRI. The development may impact clinical practice by providing a resource-saving and objective technology for diagnosing perineal descent in the many patients suffering from anorectal disorders. The technology may also be used in colon experiments with Fecobionics and for other gastrointestinal devices containing IMUs such as ingestible capsules like the Smartpill.

Clinical and Translational Gastroenterology 2021;12:e00342. https://doi.org/10.14309/ctg.0000000000000342

INTRODUCTION
Anorectal disorders and symptoms related to impaired defecatory function are very common (1,2). Anorectal disorders and symptoms may be associated with excessive perineal descent (also termed increased perineal descent or descending perineum syndrome). This is typically described as ballooning of the perineum several centimeters below the bony outlet of the pelvis during straining. Excessive and repetitive straining is believed to be one of the main causes of perineal descent. Other possible causes are weakness of the pelvic floor muscles caused by either neuropathic degeneration of muscle that accompanies old age, trauma to the pelvic floor muscles or their nerve supply during pregnancy and childbirth, or connective tissue disorders (3–7). Perineal descent is a common condition. Because it is often associated with fecal incontinence and obstructed defecation (8,9), it is important to have an objective, valid, and easy-to-use test not based on radiation.

A variety of technologies including manometry have been used in the gastrointestinal tract to evaluate function and mechanisms that lead to dysfunction (10,11). For example, anorectal (defecatory) function is commonly tested using pressure measurements and imaging technology including endoanal ultrasonography and defecography. The latter is the benchmark clinical technology for assessment of perineal descent, but it suffers from subjective measurements and interobserver variation (12–15). A variety of physiological tests and diagnostic procedures such as anal squeezes and straining are conducted during the testing. Because discrepancy exists between anorectal tests and the diagnostic accuracy of some tests is low (16,17), we developed a simulated stool named Fecobionics that combines anorectal manometry with the balloon expulsion test (18–20). Fecobionics has pressure sensors and contain inertial measurement units (IMUs) for measurement of orientation (Figure 1). The 2 IMUs in Fecobionics are used for computing the anorectal angle during defecation.

The availability of lightweight microelectromechanical system sensors has enabled the use of IMUs to determine physiological
bionics. The translational impact is to obtain an objective electronic maneuvers such as push, anal squeeze, and defecation of Fecobionics validated data from bench experiments as well as human data from descent using the IMU in the novel Fecobionics device. We provide computation of displacement during anorectal procedures and perineal eradication must be compensated. In this article, we present an algorithm combining ZUPT and gravity compensation, which can reduce the error caused by integration and enable displacement estimation.

The ZUPT method reduces the drift caused by integration when the IMU is stationary; otherwise, the IMU is moving (25). It is defined as:

\[ T_k(a, \omega) = \frac{1}{N} \sum_{n=k}^{N-1} \left( \frac{1}{\sigma_a^2} a_n \cdot \frac{a^2}{a} + \frac{1}{\sigma_g^2} g_n \cdot g \right) \leq \gamma \quad (1), \]

where \( \sigma_a \) is the acceleration vector \((a \in \mathbb{R}^3)\), \( \omega \) is angular velocity vector \((\omega \in \mathbb{R}^3)\), \( \sigma_a \) is the standard deviation of acceleration and angular velocity in a window of \( N \), \( \bar{a} \) is the mean acceleration, and \( g \) is the magnitude of gravitational acceleration.

Gravity compensation

The gravity compensation method by gyroscopes (GYRc) was proposed to determine the displacement in movements with rotation (22). The general principle of gravity compensation is to transfer the alignment of the gravitational acceleration vector to the sensor frame by the angular velocity acquired by gyroscope. This can be calculated as:

\[ g_t = q_t \cdot g_i^{-1} \quad (2), \]

where \( q_t \) is the rotational quaternion that are updated by the angular velocity and \( g_i \) is the initial gravitational vector. After the alignment is transferred, the actual linear acceleration of the sensor is calculated by subtracting the gravitational vector from the net acceleration by the following formula:

\[ a_{\text{linear}} = a_{\text{net}} - g_t \quad (3), \]

where \( a_{\text{linear}} \) is the actual linear acceleration. \( a_{\text{net}} \) is the net acceleration with gravitational and linear acceleration component. \( g_t \) is the gravitational vector aligned with the sensor frame.

We introduced a combined GLRT and GYRc algorithm to measure displacement. First, the GLRT method provides acceleration with zero-velocity update. Next, the GYRc method provides the update of gravitational acceleration aligned with the sensor frame. After subtracting \( g_t \), actual linear acceleration \( a_{\text{linear}} \) was obtained. \( a_{\text{linear}} \) was integrated to obtain velocity and double integrated to obtain displacement.

Robot model experiments

To evaluate the displacement determination algorithm, a robot system was constructed. To mimic the conditions \( \text{in vivo} \), the robot system performed linear and rotational movements. A 10-cm long linear ball screw slide (Manmeirui, GGP 1610, Yancheng, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration. A metal gear servo (Tower Pro, MG90S, Shenzhen, China) with a precision of \( \pm 0.05 \) mm was used. The speed of the slider was controlled by the 57*56 step motor. To control the sensor to move smoothly, the step motor was accelerated and decelerated with constant acceleration and deceleration.
defecography for validation. A small amount of contrast fluid was injected into rectum before inserting Fecobionics for improved radiographic visualization. Anal squeezes and defection of Fecobionics were also performed. The sampling rate was 30 Hz in the Fecobionics experiments. The normal subject had no defecatory symptoms and fecal incontinence severity index and Wexner constipation scoring system scores within the normal range. The 4 constipated subjects had constipation scoring system scores between 12 and 21. One patient had constipation symptoms for 18 months, whereas the others had symptoms for 6–20 years. Constipation symptoms were described as stable. All patients used laxatives on a regular basis (agiolax, lactulose, or both) without much relief of symptoms. Two of the subjects had balloon expulsion technology studies performed during the past 2 years and were not able to expel the balloon.

Statistical analysis

Statistical analysis was performed by MATLAB R2019 (Mathworks, Natick, MA). Most data were normal-distributed as verified by the Kolmogorov-Smirnov test. The correlation between the reference and measured displacement was analyzed by linear regression. The goodness of fit was evaluated by the coefficient of determination, $R^2 \in [0, 1]$. In addition, Bland-Altman analysis was performed to investigate how well the predicted displacement agreed with the reference (26). $P$ values were obtained from the Student $t$ test. $P < 0.05$ was considered statistically significant.

RESULTS

Results from the robot model experiments

In the robot experiment, the IMU was moved upward and downward in the range of 0.25 to 2.5 cm with 0.25-cm increments. The servo was programmed to rotate 30 degrees and simultaneously move vertically with an acceleration of 1 m/s$^2$. For each displacement, the experiment was repeated 20 times ($n = 200$). The IMU sampling rate was 155 Hz. Data were collected and analyzed by the proposed combined GLRT and GYRc method. The reference displacement was labeled by the programmable speed of the step motor, and the computed displacement was compared with the reference. Figure 3 shows an example of acceleration, velocity, and displacement profiles where the sensor was moved 2 cm downward followed by 2 cm upward after 2 s. Each motion was performed in 0.4 s. The left panel of Figure 3 shows the unfiltered acceleration, whereas the right panel shows the filtered signal with moving average with a window size of 5. Although the acceleration was noisy, the integrator acted as a low pass filter (27). Therefore, the velocity and displacement tracings were much smoother as shown in the upper panel of Figure 3. Hence, filtering the acceleration data was not necessary. In the example shown in Figure 3, the computed displacement fitted the reference well, i.e., the deviation of the peak displacement from reference was 0.05 cm.

The displacement in the robot experiment was analyzed by linear regression. Figure 4 shows the linear regression between the mean of computed displacement and the reference. The mean of computed displacement and reference displacement showed very good correlation with slope 1.01 ($P < 0.001$) and $R^2$ of 0.9789. The error was quantified as the root mean squared error (RMSE). A systematic increasing RMSE was found between the computed and reference displacement when the displacement was increased. The agreement between measured and real values was also studied using Bland-Altman analysis. The bias was close to zero, and SD was below 0.5 cm. During 200 displacement tests in the range of 0.25 to 2.5 cm, the average deviation between the computed displacement to the reference was $-0.04 \pm 0.498$ cm.

Results from in vivo experiments

Human experiments were conducted using the Fecobionics device. Data were obtained from the front IMU (closest to the anus) and 3 pressure sensors. The subject was instructed to do push procedures and anal squeezes several times, and the displacement was computed by the proposed method. Figure 5 shows an example of displacement analysis during 1 push and 1 anal squeeze. The displacement was computed to be $-1.6$ cm in the push and $0.9$ cm in the anal squeeze, which is in the physiological range. Negative values indicate the downward direction, and positive values indicate upward direction.

The final validation experiment was performed in the 5 human subjects with simultaneous defecography and Fecobionics. Several push procedures and anal squeezes were performed in each subject with empty or filled Fecobionics bag before the subject was asked to defeate Fecobionics. The normal subject felt urge at 60 mL bag volume, whereas all patients reached the 80 mL maximum before feeling urge, indicating hyposensitivity. One patient could not expel the Fecobionics probe within the 2-
minute limit, whereas 2 subjects unintentionally expelled it during the push procedures. The normal subject showed more displacement than the patients for anal squeezes and push procedures. Figure 6 shows defecographic images before and during push and anal squeeze and comparative data. Good agreement was found between distances measured with IMU and defecography. The slope was 0.83 ($P < 0.001$). $R^2$ was 0.79. If defecations were included in the analysis, the agreement was even better ($R^2 = 0.89$). The Bland-Altman plot showed minimal bias that clearly was within the confidence interval.

**DISCUSSION**

In this study, algorithms were developed for computation of displacement using IMUs embedded in a Fecobionics device for anorectal testing. Through several iterations, we were able to obtain acceptable measurements that fitted well to reference values. The algorithms were applied to previously obtained Fecobionics data that showed displacement data in the expected range (13–15, 28). The final validation experiments in human subjects with simultaneous defecography and Fecobionics demonstrated agreement between the 2 methods.

**Clinical aspects**

Fecobionics is a novel anorectal function test that provides measurements of pressures, bending angle (anorectal angle) and geometric profiles (18–20). It has proven useful for assessment of anorectal physiology. In addition to pressure
measurements in the direction of the trajectory, it also provides an electronically measured anorectal angle. Fecobionics has been validated in bench testing (19) and used in normal human subjects and patients (18–20,29–31). In this study, we pursued additional use of the IMU data for analysis of acceleration, velocity, and displacement of movements. The specific aim was to develop an electronic test of displacement including perineal descent that occur during push and straining. However, it will not be able to detect rectal prolapse or stationary descent (1,2,12).

Perineal descent is typically described as ballooning of the perineum several centimeters below the bony outlet of the pelvis during strain. Descent can also occur at rest. Excessive and repetitive straining is believed to be 1 of the main causes. This straining forces the anterior rectal wall to protrude into the anal canal and creates a sensation of incomplete defecation and weakness of the pelvic floor musculature. Other possible causes reported are weakness of the muscles of the pelvic floor caused by either neuropathic degeneration of muscle that accompanies old age (3–5), trauma to the pelvic floor muscles, or to their nerve supply during pregnancy and childbirth or connective tissue disease (4,6,7). Abnormal movements and perineal descent have been described in relation to anorectal disorders including constipation and fecal incontinence. Perineal descent is a common condition associated with fecal incontinence and obstructed defecation (8,9). Because it is associated with anorectal symptoms, it is important to have a valid easy-to-use test without radiation involved. In this study we demonstrated that the new technology is comparable with the benchmark clinical standard defecography. The big advantage of Fecobionics is that the IMUs provide an objective measurement of displacement including perineal descent, whereas defecography suffers from manual measurements on images and interobserver variation. Furthermore, in versions of Fecobionics that also measures cross-sectional areas and shape (18), rectal and anal diameters can be assessed. These have also be found to be comparable with diameters measured by defecography.

**Methodological aspects**

In this article, we used GLRT as the ZUPT method. Several ZUPT methods have been proposed before, including decision tree filtering method, Hidden Markov Model, and GLRT (32–34). Decision tree filtering method requires routine calibration of acceleration (32). Hidden Markov Model uses only the gyroscope for determine the movement and cannot determine a motion with no rotation (33). Therefore, these methods are not suitable for evaluation of displacement during defecatory testing, which is a dynamic process with small rotation. Good results have been reported for applying GLRT in foot-mounted systems (34). A limitation of GLRT algorithms is their threshold-based activation behavior, which is sensitive to motion type. The detection may fail if the user changes its motion type or intensity. Adaptive threshold methods by support vector machine classifier (35) have been proposed to detect multiple motion types. An adaptive threshold method could further reduce the estimation errors.

The current displacement estimation error comes from 2 sources: modeling error and measurement error. The modeling error can be reduced by choosing better models (e.g., ZUPT algorithm with a higher accuracy). The sensors themselves introduce the measurement error. This error depends on the gyro drift rate, frequency and magnitude of acceleration maneuvers, and accelerometer precision and accuracy (23). For the Gaussian white noise model proposed by Thong et al. (24), the RMSE of displacement was given by:

\[
\text{RMS}(s(T)) = \frac{1}{2} \frac{\sigma_d}{\sqrt{f_s}} T^{1.5}
\]

where \(\sigma_d\) is the SD of noise of accelerometer, which is 400 \(\mu g/\sqrt{Hz}\) from data sheet, \(f_s\) is the sampling frequency, and \(T\) is the time interval.

![Figure 5.](image-url) Velocity and displacement analysis for the in vivo experiment. Left: representative of displacement and pressure profile during a push. Right: representative of displacement and pressure profile during a squeeze. The colored tracings are explained in the figure.
is the integration time. The error increase inversely with sampling rate and proportional to $T^{1.5}$. To verify the effect of sampling frequency and integration time on the error, we conducted robot experiment where the IMU was moved 2 cm up and down. Keeping the integration time constant, the RMSE was 0.55 cm at sampling frequency 155 Hz, whereas RMSE was 1.18 cm (increased by 115%) at sampling frequency 64 Hz. Keeping the sampling frequency constant, RMSE was 0.62 cm at integration time 0.4 s, whereas RMSE was 1.55 cm (increased by 150%) at integration time 0.8 s. Hence, high sampling frequency and short integration time is required to obtain an accurate estimation of displacement. The human experiments were performed at a considerable lower frequency. Therefore, results can be further improved by using better IMUs and higher data transmission rate.

Our results from the robot experiments showed the combined GLRT and GYRc method was able to accurately predict displacements ranging from 0.25 to 2.5 cm in a movement with rotation. It demonstrated the potential of measuring the displacement of perineal descent *in vivo*. However, we found the SD to be 0.498 cm in the computed displacement. This means multiple inspections are required to obtain a precise measurement of displacement. By using the mean displacement from multiple inspections, the error can be greatly reduced.

As expected, we showed agreement between defecography as the benchmark reference and the new IMU-based technology. However, the sampling frequency used in Fecobionics was merely 30 Hz. According to Eq. 4, the RMSE is inversely proportional to the square root of the sampling frequency. Therefore, the results could have been even better with a system based on higher frequency.

**CONCLUSIONS**

In this study, we provide bench test validation and found a high degree of agreement between defecography and IMU-based measurement of movements of the pelvic floor. With further
improvement in technology including using better IMUs and higher sampling frequencies, the test may prove useful for addressing the critical medical need for objective evaluation of displacements during defecation and perineal descent. Another highly relevant translational impact is application of the technology to passage of Fecobionics in colon (36) or to ingestible capsules that contain IMUs.

CONFLICTS OF INTEREST
Guarantor of the article: Hans Gregersen, MD, PhD.
Specific author contributions: All authors participated in the experimental work, commented on the data, and read and approved the final manuscript. Analysis was performed by Z.Z., H.Y.H. and H.G. Study design and planning were performed by Z.Z., H.G., and K.F. H.G. drafted the manuscript.
Financial support: The Chinese University of Hong Kong (strategic recruitment funding) and RCG grant #14106717.
Potential competing interests: H.G. invented the Fecobionics device and filed patent applications.

ACKNOWLEDGEMENTS
M.Sci. Tianle Pan is kindly thanked for revision of the manuscript.

Study Highlights

WHAT IS KNOWN

✓ Perineal descent is traditionally measured from defecographic images
✓ Defecography is subjected to interobserved bias

WHAT IS NEW HERE

✓ A method for electronic measurement of perineal descent using inertial measurement units was developed
✓ The technique was validated in vitro, and human experiments correlated well with defecographic assessment

TRANSLATIONAL IMPACT

✓ The development may impact clinical practice by providing an easy-to-use, resource-saving, and objective technology for diagnosing perineal descent in the many patients suffering from anorectal disorders.
✓ The technology may be used in devices placed in colon or ingestible capsules for evaluation of gastrointestinal physiology.

REFERENCES

1. Rao SS, Bharucha AE, Chiarioni G, et al. Functional anorectal disorders. Gastroenterology 2016;150:1430–42.
2. Bharucha AE, Wald A, Enck P, et al. Functional anorectal disorders. Gastroenterology 2006;130:1510–8.
3. Laurberg S, Swash M. Effects of aging on the anorectal sphincters and their innervation. Dis Colon Rectum 1989;32:737–42.
4. Ryhammer AM, Laurberg S, Sørensen FH. Effects of age on anal function in normal women. Int J Colorectal Dis 1997;12:225–9.
5. Tomlinson BE, Walton JN, Rebeiz JJ. The effects of ageing and of cachexia upon skeletal muscle. A histopathological study. J Neurol Sci 1969;9:321–46.
6. Parks AG, Swash M, Urich H. Sphincter denervation in anorectal incontinence and rectal prolapse. Gut 1977;18:656–65.
7. Wang XJ, Chedid V, Vijayvargiya P, et al. Clinical features and associations of descending perineum syndrome in 300 adults with constipation in gastroenterology referral practice. Dig Dis Sci 2020;65:3688–95.
8. Foxx-Orenstein AE, Umar SB, Crowell MD. Common anorectal disorders. Gastroenterol Hepatol 2014;10:294–301.
9. Payne I, Grimm LM. Functional disorders of constipation: Paradoxical puborectalis contraction and increased perineal descent. Clin Colon Rectal Surg 2017;30:22–9.
10. Gregersen H. Biomechanics of the Gastrointestinal Tract. Springer Verlag: London, UK, 2002.
11. Gregersen H, Christensen J. Clinical Biomechanics in the Gut. An Introduction. Bentham Science Publishers: Sharjah, United Arab Emirates, 2016.
12. Barleben A, Mills S. Anorectal anatomy and physiology. Surg Clin North Am 2010;90:1–5.
13. Tirunamanisetty P, Prichard D, Fletcher JG, et al. Normal values of assessment of anal sphincter morphology, anorectal motion, and pelvic organ prolapse with MRI in healthy women. Neurogastroenterol Motil 2018;30:e1314.
14. Bharucha AE. Update on tests of colon and rectal structure and function. J Clin Gastroenterol 2006;40:96–103.
15. Mahieu P, Pringot J, Bodart P. Defecography: I. Description of a new procedure and results in normal patients. Gastrointest Radiol 1984;9:247–51.
16. Palit S, Thin N, Knowles CH, et al. Diagnostic disagreement between tests of evacuatory function: A prospective study of 100 consecutive patients. Neurogastroenterol Motil 2016;28:1589–98.
17. Grossi U, Carrington EV, Bharucha AE, et al. Diagnostic accuracy study of anorectal manometry for diagnosis of dysyneural feces. Gut 2016;65:447–55.
18. Gregersen H, Krogh K, Liao D. Fecobionics: Integrating anorectal function measurements. Clin Gastroenterol Hepatol 2018;16(6):981–3.
19. Sun D, Huang Z, Zhuang Z, et al. Fecobionics: A novel bionics device for studying defecation. Ann Biomed Eng 2019;47:576–89.
20. Gregersen H, Chen SC, Leung WW, et al. Novel Fecobionics defecatory function testing. Clin Transl Gastroenterol 2019;10(12), e00108.
21. Victorino MN, Jiang X, Menon C. Wearable Technologies and Force Myography for Healthcare. Elsevier Inc., 2018. (https://doi.org/10.1016/b978-0-12-811810-8.00007-5).
22. Krogh MR, Nghiemi GM, Halvorsen PS, et al. Gravity compensation method for combined accelerometer and gyro sensors used in cardiac motion measurements. Ann Biomed Eng 2017;45:1292–304.
23. Foxlin E. Pedestrian tracking with shoe-mouted inertial sensors. IEEE Comput Graph Appl 2005;38–46.
24. Thong YK, Woolson MS, Crowe JA, et al. Dependence of inertial measurements of distance on accelerometer noise. Meas Sci Technol 2002;13:1163–72.
25. Skog I, Händel P, Skog I, et al. Zero-velocity detection—an algorithm evaluation zero-velocity detection. IEEE Trans Biomed Eng 2010;57:2657–66.
26. Bland JM, Altman DG. Statistical methods for assessing agreement between 2 methods of clinical measurement. Lancet 1986;1:307–10.
27. Tavares SE. A comparison of integration and low-pass filtering. IEEE Trans Instrum Meas 1966;15:33–8.
28. Van Koughnett JAM, da Silva G. Anorectal physiology and testing. Gastroenterol Clin North Am 2013;42:713–28.
29. Gregersen H, Chen SC, Leung WW, et al. Fecobionics characterization of patients with fecal incontinence. Clin Gastroenterol Hepatol, in press.
30. Gregersen H. Fecobionics: A novel bionic test of anorectal function and defecation. Gastroenterology 2017;152(Suppl 1):S317.
31. Liao D, Chen AS, Lo KM, et al. Theoretical tools to analyze anorectal mechanophysiological data generated by the Fecobionics device. J Biomech Eng 2019;141:0945011
32. Coyte JL, Stirling D, Ros M, et al. Displacement profile estimation using low cost inertial motion sensors with applications to sporting and rehabilitation exercises. In 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM). 2013, pp 1290–5.
33. Park SK, Suh YS. A zero velocity detection algorithm using inertial sensors for pedestrian navigation systems. Sensors (Switzerland) 2010;10:9163–78.
34. Gupta AK, Skog I, Handel P. Long-term performance evaluation of a foot-mounted pedestrian navigation device. 12th IEEE Int Conf Electron Energy Environ Commun Comput Control (E3-C3), INDICON, 2015, pp 1–6. (https://doi.org/10.1109/INDICON.2015.7443478).

35. Wagstaff B, Peretroukjin V, Kelly J. Improving foot-mounted inertial navigation through real-time motion classification. Proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN’17), 2017. (https://doi.org/10.1109/IPIN.2017.8115947).

36. Gregersen H, Wang Y, Guo X, et al. Simulated colonic feces reveals novel contraction patterns. Gastroenterology 2021;160(3):660–2.

Open Access This is an open access article distributed under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 (CCBY-NC-ND), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.