Fiber Optic-embedded Gait-Tracking Insole for Detection of Toe-Walking in Children with Autism Spectrum Disorder

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Background and Purpose Toe-walking is defined as a bilateral toe-to-toe walking pattern of children without heel strike at the initiation of a stance (Ruzbarsky et al., 2016). It is often related to developmental or neurological disorders – 20.1% of children with autism spectrum disorder show persistent toe walking (Barrow et al., 2011), which can make heel cords tight, limit ankle dorsiflexion, cause pain around the foot and ankle, and lead to compensatory abnormal gaits, which is evidence of children's development of abnormal gaits, increasing physiological and psychological distress of the child and the family (Barrow et al., 2011; Ruzbarsky et al., 2016). Daily, and home-basis gait pattern monitoring is necessary to track the condition before/during/after interventions; the importance of this is increasing during the pandemic when children cannot visit clinics as much as they used to.

Currently available foot pressure sensors, however, are often uncomfortable, unreliable, or unaffordable. Most of the commercially available gait-sensing devices take advantage of the electric change of conductive materials directly caused by foot pressure. The quality of the data is subject to changes in humidity or temperature. Furthermore, thin dielectric film layer, which is a common interface, is unbreathable, slippery, and susceptible to folding, which often occurs around the edge of the film under active movements. Heavy data collectors and transmitters tethered with cables between the ankle and waist are another disadvantage which limits the simulation of natural walking, and they are available almost only in a lab setting. Last, there are concerns about the reliability of even well-known products with high fidelity that are on the market (Woodburn & Helliwell, 1996).

Recent reviews on wearable and textile-compatible sensors include fiber optics as an alternative to the conventional conductivity-based sensors, based on their stability against chemical/temperature changes and electromagnetic interference (Sanchez et al., 2021). Conventional fiber optics made of glass or plastic are highly effective in light transmittance in ideal conditions without application of physical stress and strain. But the light transmittance through fiber optics is sensitive and responsive to physical stress such as elongation, compression and deformation. Such a responsive physical property indicates the potential of fiber optics as a sensor. Considering this unique responsive property, this study aims to develop a user-friendly insole as wearable gait-monitoring system to track toe-walking patterns by using optical fibers.

Design The insole developed for this study uses the change in intensity of light inside stretchable optical fibers (LightLace^{TM}, Organic Robotics Co., NY). Four optical fibers were placed parallel to the foot axis and four others were placed parallel across the axis, so that when the foot presses down, the intersections create dents in the fibers (Figure 1A). The light inside of the fiber leaks around the dents, and represents the level of pressure. The four optical fibers which are perpendicular to the foot axis react to the plantar pressure of four locations: heel, midfoot, ball and toe respectively, so that the device not only detects toe walking but also the general sequence of a stance. An infrared LED (Light Emitting Diode) and a photodiode were connected to each side of the optical fibers through 3D printed connectors. Blocks made of an EVA foam board buffers the foot pressure around each optical fiber to prevent the light from being completely lost. On top of that, a soft EVA foam floor enhanced user comfort. In summary, the dents created around the intersections of the optical fibers under the foot pressure were the main cause of the decrease the light intensity, and the photodiode detected the change, which affected the voltage readings.

Method A microcontroller (Arduino Nano, Arduino) collected the voltage changes triggered by

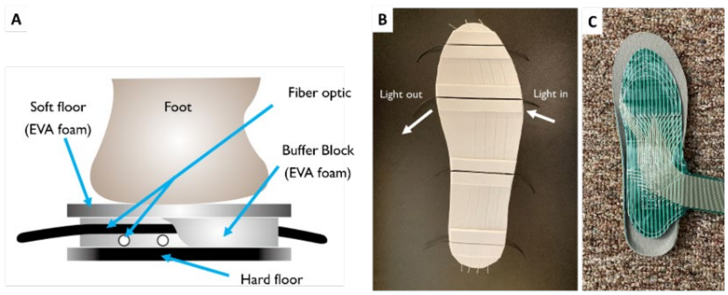
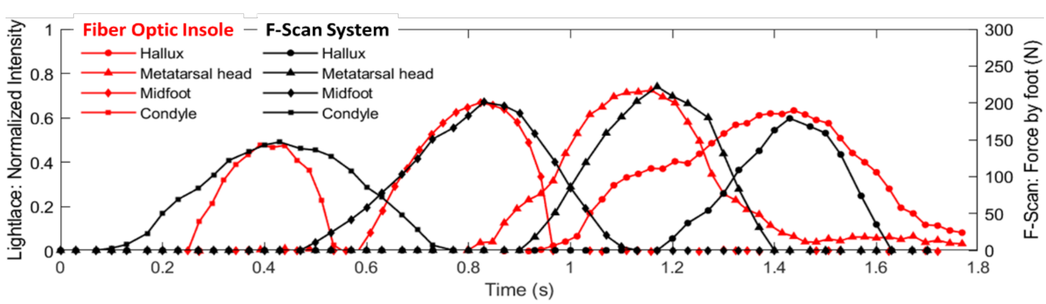


Figure 1. (a) Structure and design of the insole, (b) Sensor arranged on the insole, (c) Test setting.

the plantar pressure from the photodiode. To access the reliability of the fiber optic sensor, we used a commercially available plantar pressure sensor (F-Scan System, Tekscan Inc., Boston, MA) on top of the soft floor of the insole (Figure 1C). Since each fiber represents only a thin area of each location, we defined the same area using the software of the F-Scan system to get the corresponding foot pressure. For this preliminary test, one of the researchers walked randomly on the insole for 30 seconds. The test was repeated five times.

Result The mean and standard deviation of the correlation coefficient (r^2) of the fiber optic sensor signal and F-Scan data were 0.784 (Hallux, SD: 0.08), 0.944 (Metatarsal head, SD: 0.02), 0.810 (Midfoot, SD: 0.09), and 0.862 (Condyle, SD: 0.05) respectively. Figure 2 is the data trend of one of the stances, which shows and represents time and amount of the peak points from the two sensors matched at all locations.

Figure 2. Comparison of the result between the insole and F-Scan



Discussion Even though the correlation at two locations went under 0.7 only at the first trial, the overall performance of the fiber optic-based insole demonstrated a potential of the prototype to track the toe walking pattern of a child in various locations for the possibility of consistent and continuous monitoring of children's gait patterns, as an alternative to existing technologies that can be used in only clinical settings. The mis-matching of the signal come mostly from the difference of the start/end point of the pressure, which may be because that the optical fibers parallel to the foot axis lean to the outside of the foot. Testing with only one adult is a clear limitation of the present study, which raises the need to examine the practicality on the actual population – children with autism spectrum disorder. Future studies need to evaluate the speed of recovery of the fibers from the dents when a user wears them for several hours, to guarantee the sensor's reliability over a whole day. Another promising area of research would be to explore opportunities to measure the plantar pressure in 2D throughout the foot sole or to integrate fiber optics into socks or shoes.

References

Barrow, W. J., Jaworski, M., & Accardo, P. J. (2011). Persistent Toe Walking in Autism. *Journal of Child Neurology*, *26*(5), 619–621. https://doi.org/10.1177/0883073810385344

Dietz, F., & Khunsree, S. (2012). Idiopathic Toe Walking: To Treat or not to Treat, that is the Question. *The Iowa Orthopaedic Journal*, *32*, 184–188.

Gong, Z., Xiang, Z., OuYang, X., Zhang, J., Lau, N., Zhou, J., & Chan, C. C. (2019). Wearable Fiber Optic Technology Based on Smart Textile: A Review. *Materials*, *12*(20), 3311.

Ruzbarsky, J. J., Scher, D., & Dodwell, E. (2016). Toe walking: Causes, epidemiology, assessment, and treatment. *Current Opinion in Pediatrics*, *28*(1), 40–46. https://doi.org/10.1097/MOP.0000000000000302

Sanchez, V., Walsh, C. J., & Wood, R. J. (2021). Textile Technology for Soft Robotic and Autonomous Garments. *Advanced Functional Materials*, *31*(6), 2008278. https://doi.org/10.1002/adfm.202008278

Woodburn, J., & Helliwell, P. (1996). Observations on the F-Scan in-shoe pressure measuring system. *Clinical Biomechanics*, *11*(5), 301–304. https://doi.org/10.1016/0268-0033(95)00071-2