Proceedings of the 2025 Design of Medical Devices Conference
DMD2025
April 28-30, 2025, Minneapolis, MN, USA

DMD2025-1XXX

INTELLIGENT SQUARE STEPPING EXERCISE SYSTEM FOR COGNITIVE-MOTOR REHABILITATION IN OLDER ADULTS WITH MULTIPLE SCLEROSIS

Xiaorui Gu
University of Illinois Urbana-Champaign
Urbana, IL

Prakhar Gupta
University of Illinois Urbana-Champaign
Urbana, IL

Junmin Liu
University of Illinois Urbana-Champaign
Urbana, IL

Hank Zhou
University of Illinois Urbana-Champaign
Urbana, IL

Brian Cisto
University of Illinois Urbana-Champaign
Urbana, IL

Mohammad Afzal Khan
University of Illinois Urbana-Champaign
Urbana, IL

Sam Mason
University of Illinois Urbana-Champaign
Urbana, IL

Robert Motl, PhD
University of Illinois Chicago
Chicago, IL

Emerson Sebastiao, PhD
University of Illinois Urbana-Champaign
Urbana, IL

Manuel E. Hernandez, PhD
University of Illinois Urbana-Champaign
Urbana, IL

ABSTRACT

The Intelligent Square Stepping Exercise System is designed to facilitate cognitive-motor rehabilitation for older adults with Multiple Sclerosis (MS). This innovative system includes a smart mat equipped with pressure sensors and real-time feedback capabilities, addressing the limitations of traditional square stepping exercises. The mat is lightweight, portable, and features an anti-slip surface for enhanced safety. A dedicated data processing unit processes sensor inputs and communicates with users via a mobile interface. Testing demonstrated accurate step detection, effective feedback delivery, and overall system reliability. The project achieved key milestones in usability, portability, and system integration, while identifying areas for future improvement, including manufacturing quality, sensitivity tuning, and user interface enhancements. This system offers a promising solution for safe and accessible rehabilitation for individuals with MS, addressing their unique needs.

Keywords: multiple sclerosis, rehabilitation, health devices

1. INTRODUCTION

The proposed research addresses a critical public health and clinical care problem – aging with a chronic, neurologic disabling disease, namely multiple sclerosis (MS). Of the over 1 million adults living with MS in the United States, 1 in 4 are over the age of 60 years[1–3]. Older adults with MS (OAMS) are an under-researched but rapidly expanding segment of the MS population [1,3,4]. OAMS experience a higher burden of physical and cognitive challenges than younger adults with MS and age-matched controls without MS [5–7]. Remarkably, 75% of OAMS have limitations in walking just 100 meters [8], and approximately 77% demonstrate cognitive impairment on neuropsychological assessments [9], creating a high level of dependence for activities of daily living [10–14]. There is further evidence of lifespan declines in physical, walking, and cognitive performance [15–18], and faster rate of disease progression among OAMS [19]. This is a collective concern as physical and cognitive function are paramount for independence and quality of life (QOL), and creates a crisis wherein healthcare providers have limited resources for managing the problems of aging with MS.

To date, there is limited data on the efficacy of FDA-approved disease-modifying therapies (1st line of treatment) for managing disease progression over time and physical and cognitive outcomes in OAMS [20–22]. One solution to fulfill the absence of effective treatments involves identifying new rehabilitation approaches, including novel and remotely delivered exercise training interventions, for managing the consequences of aging with MS and ultimately improve participation and QOL in this population. We have previously conducted a feasibility trial of a hybrid (lab practice followed by home-based training) square stepping exercise (SSE) intervention in OAMS [23]. SSE is performed on a 4’ by 8’ foot mat that is separated in 40 smaller squares and involves prescribed stepping sequences as an exercise modality, while requiring cognitive function by including elements of recall memory, executive function, visuospatial function, and analogy for reproducing a given sequence of step patterns. SSE has shown to be effective to improve components of physical and cognitive function in older adults from the general population [24–28], in patients with Parkinson’s disease [29], and stroke

[30]. We reported preliminary efficacy for functional mobility and cognition in our feasibility trial involving a hybrid SSE approach in 26 OAMS [23]. To date, SSE programs have been delivered either as a fully in-person intervention or as a hybrid approach [31,32]. The hybrid process, of note, requires that researchers demonstrate step patterns that participants learn in the lab and then printing copies of step patterns for the home-based training. Although it minimizes barriers associated with supervised exercise rehabilitation interventions it does not provide full access to those requiring transportation to exercise facilities and rehabilitation clinics, which may reduce program/treatment adherence.

Given the limited options in rehabilitation and management of physical and cognitive outcomes in OAMS, we propose a novel approach for delivering the SSE program, namely the smart SSE (sSSE) mat system that can automatically and interactively teach and monitor movement patterns during home-based SSE. Our idea of developing a smart version of the SSE program organically combines the strengths of physical exercise and cognitive rehabilitation in a single approach. This creates a more holistic approach for rehabilitation based on the PRIMERS model of brain plasticity for MS [33], which potentially offers a more comprehensive and effective approach based on central nervous system activation to address physical and cognitive impairment in OAMS and to enhance these important clinical outcomes and overall QOL in this population. The embedded motor-cognitive stimuli can further make the program more engaging and motivating and may have a broader application among different populations with overlapping symptoms. The work presented outlines prototype development and proof-of-concept testing.

2. MATERIALS AND METHODS

The idea behind the smart SSE draws upon games such as the Simon Electronic Memory Game, and Electronic Step Dancing Machines. The current design aims to facilitate physical and cognitive rehabilitation and exercise uptake among OAMS by leveraging technology that overcomes barriers associated with accessibility of onsite rehabilitation programs and exercise interventions.

2.1 Hardware Design

The system consists of a multi-layered pressure sensing mat, as depicted in Fig. 1, where custom pressure sensors on the mat can detect the user's steps. The data processing unit (DPU) controls the sensor, LEDs, and communicates wirelessly with the software on mobile devices. Mobile device software is used to monitor training results and load training plans to the DPU. An AC/DC transformer was used to supply voltage to the DPU. Also, the whole system is designed to be soft, foldable and light-weight enough to be portable by OAMS.

2.1.1 Smart Mat

The smart mat, consists of a 10 x 4 array of 30 cm x 25 cm blocks, with an overall dimension of 3 m in length and 1 m in width. The smart mat detects a user's stepping position using pressure sensors and gives visual hints and feedback using the LED arrays mounted on the mat.

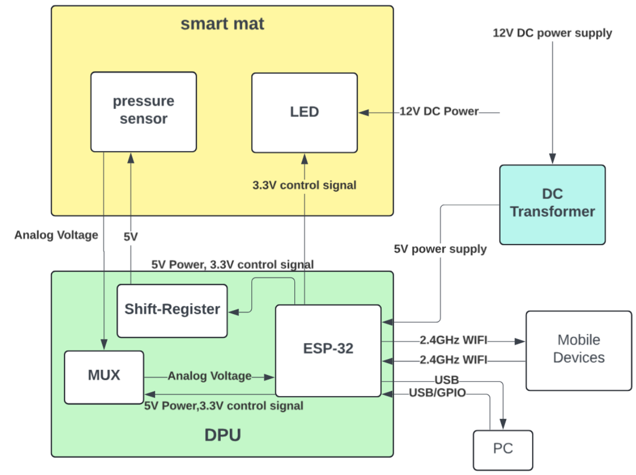

FIGURE 1: SYSTEM BLOCK DIAGRAM

The mat has 7 layers. The bottom layer is an anti-slip yoga mat, above that are 4 columns of copper film stripes as inputs, then a custom pressure sensor on the center of the blocks, and then 10 rows of copper film stripe to serve as a voltage output, then a transparent anti-slip film as protection layer, and then LED stripes, finally another protection layer on the LEDs (Fig. 2). The custom pressure sensor under each block consists of Velostat, a pressure-sensitive resistor film between conductors, to detect resistance changes reflective of a user's step on the mat. The copper stripes are then connected to the DPU.

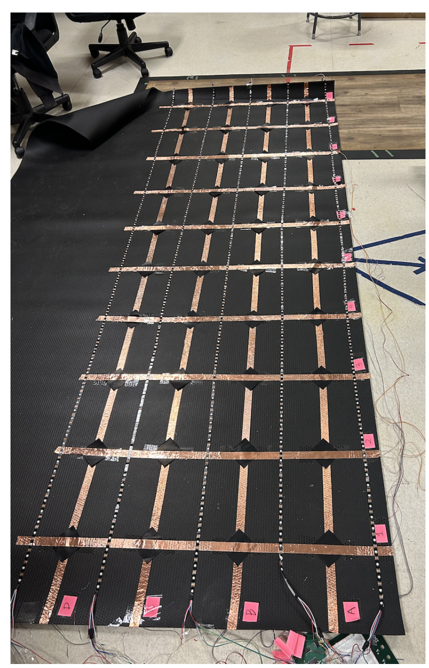

FIGURE 2: OVERVIEW OF THE SMART MAT

We used 5 programmable RGB LED stripes along the length of the mat as visual hints for users. Initially we had planned to use another 11 LED stripes along the width of each block, but this caused some wiring issues and placed additional constraints on the microprocessor. Thus, it was ultimately removed from the current prototype. The LED stripes used WS2812b individually addressable RGB LEDs. A single pin of the microprocessor was used to control a whole line of LEDs using the FastLED library. Blue tiles were used to mark the target location for each foot, and if stepped on correctly would turn green, or otherwise turn red to provide feedback to the user.

To ensure safety, we needed to make sure that the smart mat had an adequate thickness and both sides needed to be anti-slip.

2.1.2 DPU

For the data processing unit, we used a microprocessor with integrated WiFi capabilities, a shift-register to supply voltages to the pressure sensor, and a multiplexor to read voltages from the sensors. We chose to use shift-register and mux to save input/output pins of the microprocessor, and provide an additional level of protection to the microprocessor. The scanning rate of the DPU is around 10Hz, sufficiently larger than a human's walking frequency.

For the microprocessor we used an ESP32-S2-mini-1. We chose this chip because it has an integrated WiFi antenna for WiFi communications with mobile devices. We used a separate PCB for the microprocessor (Fig. 3), besides the ESP32 chip, there are some peripherals, including a programmable regulator, two buttons for reset and boot, a USB connector, and an ESD protection diode array for the USB connector. There are also some resistors and capacitors for denoising and protection.

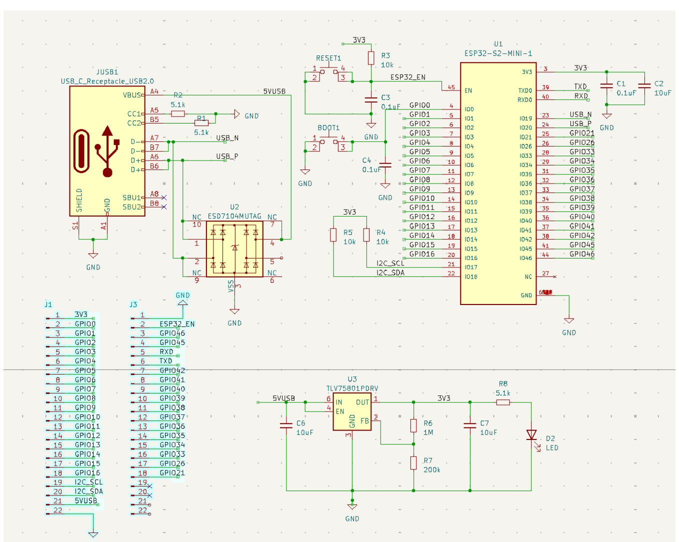

FIGURE 3: SCHEMATIC OF MICROPROCESSOR PCB

A 16-to-1 analog multiplexor CD74HC4067M is used for scanning through the 10 rows and a 74HC595 8 bit shift register is used to supply power in sequence to the 4 columns (Fig. 4). When each column is powered, all rows will be scanned in sequence, repeating this cycle enables the DPU to find the position and time of each step. The mux needs 4 pins for a 4-bit selection signal and an output pin, and the shift register needs two pins for two clock signals and one pin for serial input. Therefore, using a shift register and mux reduced the number of pins to 8 instead of 14 if we directly drive the sensor. They also enable a wider range of input/output voltage by pulling up/down the voltages. On the PCB for mux and shift register we used a capacitor and a resistor to denoise the signal.

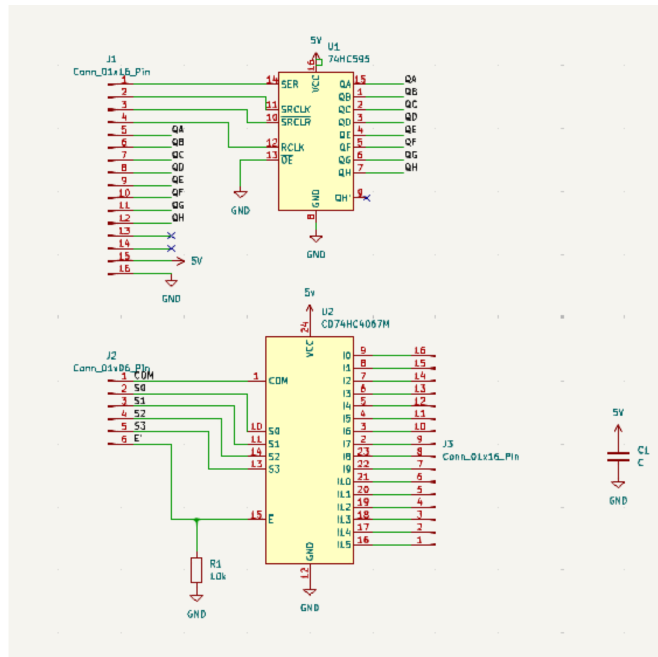

FIGURE 4: SCHEMATIC OF MULTIPLEXOR AND 8-BIT SHIFT REGISTER

The resistance of Velostat drops abruptly when pressure is increased from 0 to 2 kPa, above that range the voltage drops slowly [34]. Considering the pressure of a standing adult is usually much larger than that value, the sensor should be sensitive with steps, but cannot reflect exact pressure precisely.

An extra $1k\Omega$ resistor is used as a voltage divider. Vin is the voltage supplied to the pressure sensor and the resistor, and Vsensor is voltage across the sensor as shown in Equation 1.

$$sensor = Vin * \frac{Rsensor}{Rsensor + 1k\Omega} \quad (1)$$

For a power supply, we used an AC to DC converter to supply 12V DC to the LEDs, and a 5V regulator to supply 5 volts to the DPU.

2.2 Software Design

We used the ESP32 as a server to publish an html webpage on the local network. All the data and files are stored on the chip, while mobile devices can use HTTP requests to retrieve step data from the chip and send requests to the chip to change square stepping exercise patterns.

The user interface includes tiles representing blocks on the mat, the color of the tiles which change corresponding to the

LED colors on the mat, recording the result of the training. There are some buttons on the bottom used to load the training plans.

The system should not need internet access to operate, just a local network connection. However, during testing, we found out that the library requires internet connection even if it's not using the internet. Our team then pursued the development of a native iOS application using Bluetooth communication (see Fig. 5).

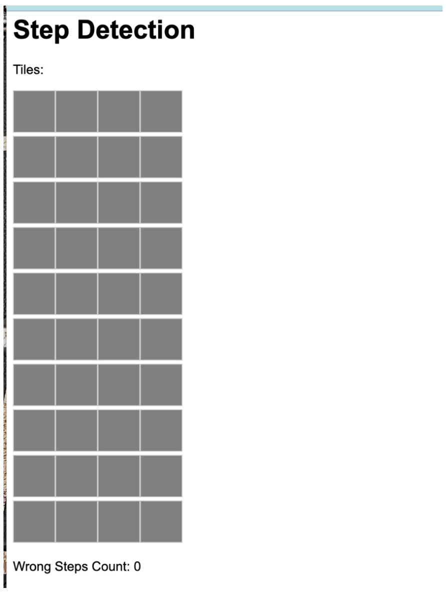

FIGURE 5: INITIAL MOBILE USER INTERFACE

The iOS application leverages Bluetooth Low Energy (BLE) to establish a stable connection between the smart mat and the mobile device. The mat, equipped with pressure-sensitive squares, registers the location and timing of each step the patient takes. During each workout, the application receives data from the mat, capturing specific metrics such as step accuracy, pressure distribution, and adherence to prescribed exercise patterns. Ensuring low-latency data transmission was crucial to provide immediate feedback to users, allowing them to adjust their steps and improve movement precision as they progress through each session. By implementing a custom communication protocol tailored to the BLE capabilities of the mat, the system ensures robust, real-time data transfer, which is essential for maintaining accuracy and reliability in therapeutic settings.

The app is programmed to guide patients through a progressive series of exercises that focus on balance, coordination, and motor control. These exercises are displayed on the mobile interface, which uses a combination of visual cues and haptic feedback to prompt patients on where and when to step. The sequence and intensity of exercises are designed in collaboration with physical therapists specializing in multiple sclerosis rehabilitation, ensuring that each workout is clinically appropriate and aligned with therapeutic goals. The system also adjusts the difficulty of the exercises based on patient performance, enabling a personalized and adaptive approach to rehabilitation.

Data from each session is processed and stored locally on the device, with provisions for secure cloud backup in future iterations. The app analyzes workout data to provide patients and healthcare providers with comprehensive feedback on motor function metrics. Key metrics tracked include step accuracy, reaction time, balance stability, and completion rate of exercises. By visualizing this data in an accessible format, the app helps patients track their improvement over time and enables clinicians to assess the efficacy of the prescribed exercise regimen. The app's architecture is modular, allowing for easy integration of additional metrics or analysis tools as the project evolves.

The user interface has been designed with an emphasis on accessibility and ease of use, ensuring that it meets the needs of patients with varying levels of motor impairment. The app employs a clean, intuitive layout that minimizes navigation complexity, allowing patients to start, pause, or end workout sessions effortlessly. Visual feedback is provided during workouts, displaying real-time metrics such as step accuracy and timing, which helps patients monitor their performance and make immediate adjustments. The interface also incorporates customizable color schemes and font sizes to accommodate visual impairments, a common symptom among OAMS.

3. RESULTS AND DISCUSSION

The accuracy of step detection was tested by having users perform a sequence of predefined stepping patterns on the mat. Each step's position and timing were logged and compared to the expected outputs. To ensure comprehensive testing, participants of varying weights and step styles were involved. The results demonstrated that the system achieved an accuracy of over 95%, surpassing the 90% minimum requirement. Minor deviations were observed, which were attributed to uneven pressure distribution on the sensor cells. Voltage readings from the pressure sensors during idle and active states were recorded and analyzed. For example, when idle, the voltage for Output Pin B, Pin 2 was 1016 mV, and when stepped on, it increased to 2922 mV. These results confirmed the reliability of the pressure sensors.

The response time for providing feedback was evaluated using a timer to measure the delay between a step on the mat and the display of feedback on the mobile interface. The system exhibited a delay of approximately 5 seconds for the initial step, while subsequent steps consistently delivered feedback within an average of 1 second. This performance comfortably met the requirement of a maximum 10-second delay.

Portability was assessed by measuring the weight of the mat using a standard scale and evaluating its ease of folding and rolling. The final weight of the mat was recorded at 12 kg, significantly below the 30 kg limit. The mat could be easily rolled and stored in a compact form, demonstrating its portability.

Durability and flexibility could be further improved by replacing parts of the copper stripes with wires, especially since thin copper stripes can wear out from repeated folding.

Individually insulated wires provides better resistance to bending and rolling without breaking, making the mat more reliable over time.

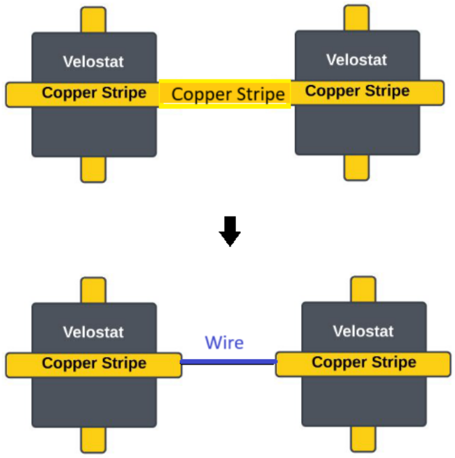

FIGURE 6: POTENTIAL IMPROVEMENTS REDARDING DURABILITY

4. CONCLUSION

Overall, this proof-of-concept study demonstrates how a smart mat can detect steps with accuracy, provide feedback to users after each step, and provide wireless transmission to a mobile device for use in potential at-home motor-cognitive training. Future work will focus on improving processing efficiency while maintaining consistency, and improvement of the quality and durability of the mat (see Fig. 6). The user interface will also undergo enhancements to provide a more intuitive and user-friendly experience. Balancing portability with safety and durability will remain a key focus to further improve the system's usability for OAMS.

ACKNOWLEDGEMENTS

This work was supported in part by the University of Illinois Chicago-University of Illinois Urbana-Champaign Applied Health Sciences Interdisciplinary Collaborative Grant Program and Department of Electrical and Computer Engineering at the University of Illinois Urbana-Champaign. .

REFERENCES

[1] Wallin, M. T., Culpepper, W. J., Campbell, J. D., Nelson, L. M., Langer-Gould, A., Marrie, R. A., Cutter, G. R., Kaye, W. E., Wagner, L., Tremlett, H., Buka, S. L., Dilokthornsakul, P., Topol, B., Chen, L. H., and Larocca, N. G., 2019, "The Prevalence of MS in the United States: A Population-Based Estimate Using Health Claims Data," Neurology. https://doi.org/10.1212/WNL.0000000000007035.

[2] Dilokthornsakul, P., Valuck, R. J., Nair, K. V., Corboy, J. R., Allen, R. R., and Campbell, J. D., 2016, "Multiple Sclerosis Prevalence in the United States Commercially Insured Population," Neurology. https://doi.org/10.1212/WNL.0000000000002469.

[3] NARCOMS, 2020, "Aging With Multiple Sclerosis," NARCOMS NOW, **9**(1), pp. 4–8.

[4] Hittle, M., Culpepper, W. J., Langer-Gould, A., Marrie, R. A., Cutter, G. R., Kaye, W. E., Wagner, L., Topol, B., LaRocca, N. G., Nelson, L. M., and Wallin, M. T., 2023, "Population-Based Estimates for the Prevalence of Multiple Sclerosis in the United States by Race, Ethnicity, Age, Sex, and Geographic Region," JAMA Neurol. https://doi.org/10.1001/jamaneurol.2023.1135.

[5] Bollaert, R. E., Balto, J. M., Sandroff, B. M., Chaparro, G., Hernandez, M. E., and Motl, R. W., 2017, "Preliminary Evidence For The Effects Of Aging And Multiple Sclerosis On Cognitive Performance: An Analysis Based On Effect Size Estimates," Exp Aging Res, **43**(4), pp. 346–354. https://doi.org/10.1080/0361073X.2017.1333820.

[6] Bollaert, R., therapy, R. M.-J. of geriatric physical, and 2019, undefined, "Physical and Cognitive Functions, Physical Activity, and Sedentary Behavior in Older Adults with Multiple Sclerosis," journals.lww.com. [Online]. Available: https://journals.lww.com/jgpt/fulltext/2019/10000/physical_and_cognitive_functions,_physical.14.aspx. [Accessed: 15-May-2022].

[7] Motl, R. W., Chaparro, G., Hernandez, M. E., Balto, J. M., and Sandroff, B. M., 2018, "Physical Function in Older Adults with Multiple Sclerosis: An Application of the Short Physical Performance Battery," Journal of Geriatric Physical Therapy, **41**(3), pp. 155–160. https://doi.org/10.1519/JPT.0000000000000115.

[8] Klewer J, Pohlau D, Nippert I, Haas J, K. J., 2001, "Problems Reported by Elderly Patients with Multiple Sclerosis," Journal of Neuroscience, **33**(3), pp. 167–171.

[9] Mariana Branco, Luis Ruano, Emilio Portaccio, Benedetta Goretti, Claudia Niccolai, Francesco Patti, Clara Chisari, Paolo Gallo, Paola Gross, Angelo Ghezzi, Marco Roscio, Flavia Mattioli, Fabio Bellomi, Marta Simone, Rosa Gemma Viterbo, M. P. A., 2019, "Aging with Multiple Sclerosis: Prevalence and Profile of Cognitive Impairment," Neurological Sciences, **40**(8), pp. 1651–1657.

[10] Bove, R., Musallam, A., Healy, B. C., Houtchens, M., Glanz, B. I., Khoury, S., Guttmann, C. R., De Jager, P. L., and Chitnis, T., 2013, "No Sex-Specific Difference in Disease Trajectory in Multiple Sclerosis Patients before and after Age 50.," BMC Neurol, **13**, p. 73. https://doi.org/10.1186/1471-2377-13-73.

[11] Dilorenzo, T., Halper, J., and Picone, M. A., 2003, "Reliability and Validity of the Multiple Sclerosis Quality of Life Inventory in Older Individuals.," Disabil Rehabil, **25**(16), pp. 891–897. https://doi.org/10.1080/0963828031000122195.

[12] Finlayson, M., 2004, "Concerns about the Future among Older Adults with Multiple Sclerosis," The American

journal of occupational therapy, **58**(1), pp. 54–63. [Online]. Available: http://ajot.aotapress.net/content/58/1/54.short.

[13] Finlayson, M., and van Denend, T., 2003, “Experiencing the Loss of Mobility: Perspectives of Older Adults with MS.,” Disabil Rehabil, **25**(20), pp. 1168–80. https://doi.org/10.1080/09638280310001596180.

[14] Jones, K. H., Ford, D. V, Jones, P. A., John, A., Middleton, R. M., Lockhart-Jones, H., Peng, J., Osborne, L. A., and Noble, J. G., 2013, “How People with Multiple Sclerosis Rate Their Quality of Life: An EQ-5D Survey via the UK MS Register.,” PLoS One, **8**(6), p. e65640. https://doi.org/10.1371/journal.pone.0065640.

[15] Jeng, B., Šilić, P., Bollaert, R. E., Sandroff, B. M., and Motl, R. W., 2023, “Physical Function across the Lifespan in Adults with Multiple Sclerosis: An Application of the Short Physical Performance Battery,” Mult Scler Relat Disord, **73**. https://doi.org/10.1016/j.msard.2023.104624.

[16] Jones, C. D., Cederberg, K. L., Sikes, E. M., Wylie, G. R., Motl, R. W., and Sandroff, B. M., 2020, “Walking and Cognitive Performance in Adults with Multiple Sclerosis: Do Age and Fatigability Matter?,” Mult Scler Relat Disord, **42**. https://doi.org/10.1016/j.msard.2020.102136.

[17] Baird, J. F., Cederberg, K. L. J., Sikes, E. M., Silveira, S. L., Jeng, B., Sasaki, J. E., Sandroff, B. M., and Motl, R. W., 2019, “Physical Activity and Walking Performance across the Lifespan among Adults with Multiple Sclerosis,” Mult Scler Relat Disord, **35**. https://doi.org/10.1016/j.msard.2019.07.003.

[18] Baird, J. F., Cederberg, K. L. J., Morghen Sikes, E., Jeng, B., Sasaki, J. E., Sandroff, B. M., and Motl, R. W., 2019, “Changes in Cognitive Performance With Age in Adults With Multiple Sclerosis,” Cogn Behav Neurol, **32**(3), p. 201. https://doi.org/10.1097/WNN.0000000000000200.

[19] Trojano, M., and Liguori, M., 2002, “Age-related Disability in Multiple Sclerosis,” Ann Neurol, **51**(4), pp. 475–480. https://doi.org/10.1002/ana.10147.

[20] Shirani, A., Zhao, Y., Petkau, J., Gustafson, P., Karim, M. E., Evans, C., Kingwell, E., van der Kop, M. L., Oger, J., and Tremlett, H., 2015, “Multiple Sclerosis in Older Adults: The Clinical Profile and Impact of Interferon Beta Treatment,” Biomed Res Int, **2015**, pp. 1–11. https://doi.org/10.1155/2015/451912.

[21] Claflin, S. B., Broadley, S., and Taylor, B. V., 2019, “The Effect of Disease Modifying Therapies on Disability Progression in Multiple Sclerosis: A Systematic Overview of Meta-Analyses,” Front Neurol. https://doi.org/10.3389/fneur.2018.01150.

[22] Burks, J., Marshall, T. S., and Ye, X., 2017, “Adherence to Disease-Modifying Therapies and Its Impact on Relapse, Health Resource Utilization, and Costs among Patients with Multiple Sclerosis,” ClinicoEconomics and Outcomes Research. https://doi.org/10.2147/CEOR.S130334.

[23] Sebastião, E., McAuley, E., Shigematsu, R., Adamson, B. C., Bollaert, R. E., and Motl, R. W., 2018, “Home-Based, Square-Stepping Exercise Program among Older Adults with Multiple Sclerosis: Results of a Feasibility Randomized Controlled Study,” Contemp Clin Trials, **73**(June), pp. 136–144. https://doi.org/10.1016/j.cct.2018.09.008.

[24] Shigematsu, R., and Okura, T., 2006, “A Novel Exercise for Improving Lower-Extremity Functional Fitness in the Elderly,” Aging Clin Exp Res, **18**(3), pp. 242–248. https://doi.org/10.1007/BF03324655.

[25] Shigematsu, R., Okura, T., Sakai, T., and Rantanen, T., 2008, “Square-Stepping Exercise versus Strength and Balance Training for Fall Risk Factors.,” Aging Clin Exp Res, **20**(1), pp. 19–24. https://doi.org/10.1007/BF03324743.

[26] Shigematsu, R., 2014, “Effects of Exercise Program Requiring Attention, Memory and Imitation on Cognitive Function in Elderly Persons: A Non-Randomized Pilot Study,” J Gerontol Geriatr Res, **03**(02). https://doi.org/10.4172/2167-7182.1000147.

[27] Shigematsu, R., Okura, T., Nakagaichi, M., Tanaka, K., Sakai, T., Kitazumi, S., and Rantanen, T., 2008, “Square-Stepping Exercise and Fall Risk Factors in Older Adults: A Single-Blind, Randomized Controlled Trial,” Journals of Gerontology - Series A Biological Sciences and Medical Sciences, **63**(1), pp. 76–82. https://doi.org/10.1093/gerona/63.1.76.

[28] Shigematsu, R., Okura, T., Nakagaichi, M., Tanaka, K., Sakai, T., Kitazumi, S., and Rantanen, T., 2008, “Square-Stepping Exercise and Fall Risk Factors in Older Adults: A Single-Blind, Randomized Controlled Trial,” J Gerontol A Biol Sci Med Sci, **63**(1), pp. 76–82. https://doi.org/10.1093/gerona/63.1.76.

[29] Liu, H. H., Wang, R. Y., Cheng, S. J., Liao, K. K., Zhou, J. H., and Yang, Y. R., 2022, “Effects of Square-Stepping Exercise on Executive Function in Individuals with Parkinson’s Disease: A Randomized Controlled Pilot Study,” Geriatr Nurs (Minneap), **47**, pp. 273–279. https://doi.org/10.1016/j.gerinurse.2022.08.004.

[30] Túbero, G. S., Gobbi, S., Teixeira, C. V. L., Pereira, J. R., Shigematsu, R., and Canonici, A. P., 2014, “Effects of Square Stepping Exercise in Patients with Sequel of Cerebrovascular Accident,” Fisioterapia em Movimento, **27**(2), pp. 229–237. https://doi.org/10.1590/0103-5150.027.002.ao08.

[31] Fisseha, B., Janakiraman, B., Yitayeh, A., and Ravichandran, H., 2017, “Effect of Square Stepping Exercise for Older Adults to Prevent Fall and Injury Related to Fall: Systematic Review and Meta-Analysis of Current Evidences,” J Exerc Rehabil. https://doi.org/10.12965/jer.1734924.462.

[32] Wang, Y. H., Liu, Y. H., Yang, Y. R., and Wang, R. Y., 2021, “Effects of Square-Stepping Exercise on Motor

and Cognitive Function in Older Adults — A Systematic Review and Meta-Analysis," Geriatr Nurs (Minneap), **42**(6). https://doi.org/10.1016/j.gerinurse.2021.10.022.

[33] Sandroff, B. M., Motl, R. W., Reed, W. R., Barbey, A. K., Benedict, R. H. B., and DeLuca, J., 2018, "Integrative CNS Plasticity With Exercise in MS: The PRIMERS (PRocessing, Integration of Multisensory Exercise-Related Stimuli) Conceptual Framework," Neurorehabil Neural Repair, **32**(10), pp. 847–862. https://doi.org/10.1177/1545968318798938.

[34] Bergmark Giesler, L., 2021, "Investigating Construction and Design Parameters of an Embroidered Resistive Pressure Sensor."