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碩士論文

Graduate Institute of Networking and Multimedia

College of Electrical Engineering and Computer Science

National Taiwan University

Master’s Thesis

基於壓力感測之 XR 視覺回饋強化太極推手練習

Enhancing Tai Chi Pushing Hands Practice with XR Visualization Feedback from Pressure Sensing

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中華民國 114 年 7 月

July 2025

doi:10.6342/NTU202503584

Acknowledgements

終於完成了這本碩士論文，也代表著我碩士生涯的結束。首先，我要深深感謝我的指導教授洪一平老師，在整個碩士過程中給予我無微不至的關懷與寶貴的指導。老師也不吝推薦對我身心有益的活動，如斷食體驗營與太極課程，這些都促成了本篇論文的誕生。我要特別感謝我們的推手教練——吳榮輝老師，謝謝您提供的專業建議與技術指導，讓我在研究過程中獲益良多。此外，也要感謝從我大學時期就一路協助我的三位重要貴人——秉軒老師、煬升學長和喬恩學姐。三位在我學術旅程中的每一階段都給予我許多幫助，也因此被我們這屆同學尊稱為「三巨頭」XD。謝謝敬媛、琪琪和宥杏，碩士期間與你們無數次有建設性的討論總是令人愉快，你們的陪伴讓研究的過程充滿動力。感謝冠廷在我設計轉困難程式時提供的 DSA 協助，我永遠不會忘記我們三天內完成 poster 並參加 SIGGRAPH SRC，竟然還拿下第三名的那段荒謬而精彩的經歷，這也是我與專業工程師合作的珍貴經驗。謝謝實驗室同屆的夥伴們，讓我在實驗室的每一天都充滿笑聲與活力。特別感謝一路從我剛加入實驗室到快畢業仍未放手的音場專案小組 XD：允玟、舒盟、成玟、丞勛和倢希。我們從一排喇叭一路打造出完整的車載影音系統，這段經歷帶來滿滿的成就感。本篇論文也要感謝 4DGS 小組的夥伴們（浩平、義峰、丞勛），有你們才成就了太極推手的 Gaussian Splatting 設計。最後，感謝我的家人與女朋友，謝謝你們在這三年中的全力支持，從未質疑我為什麼要延畢 XD。也祝福實驗室的所有夥伴們，研究順利，前程似錦！

doi:10.6342/NTU202503584

摘要

太極推手是一種強調細膩感知與內勁運用的傳統對練方式，其中「聽勁」能力對於理解與應對對方施力至關重要。然而，由於這種技巧主要靠長時間的感受和身體經驗累積，沒有明確標準可依，初學者通常不容易學會且難以量化，初學者往往難以掌握。本研究提出一套結合擴增實境（XR）與視覺回饋的訓練系統，以協助學習者在練習太極推手時更清楚地理解施力情況。我們開發了可穿戴感測袖套，內嵌壓力感測器，可即時量測對練時的接觸壓力，並將資料透過無線方式傳送至XR頭戴裝置進行視覺化。系統介面中包括動態壓力時變圖與對應手臂部位的感測位置圖，讓使用者能即時察覺自身施力情形。

我們亦透過高擬真的4D高斯潑灑技術建構虛擬教練，提供真實的動作示範，以提升學習效果。透過與太極教練的長期合作與示範實測，我們持續優化系統設計，並觀察到視覺回饋能有效幫助學習者覺察與調整動作與力道表現。未來將進一步進行正式使用者研究與硬體模組的精簡設計。本研究展示了傳統內家武術在數位技術輔助下的創新學習可能性，使抽象內勁原則得以具象化、視覺化與量化。

關鍵字：太極推手、視覺回饋、擴增實境、穿戴式感測技術、身體化學習

Abstract

Tai Chi pushing hands is a traditional partnered martial arts practice that emphasizes sensitivity to subtle forces, known as Tīng Jìng (聽勁). However, due to its internalized nature, Tīng Jìng is difficult for beginners to grasp as it requires learning experience and hard to quantify objectively. In this work, we present an extended reality (XR) system designed to enhance Tai Chi pushing hands training by providing real-time visual feedback on applied force. Our system features wearable sleeves embedded with force-sensitive resistors (FSRs) that capture pressure data during practice and transmit it wirelessly to an XR headset. The headset interface visualizes the data using time-varying plot and a pressure mapping display on a forearm illustration, helping users perceive when and where pressure is applied.

Additionally, we incorporate a photorealistic virtual coach captured using 4D Gaussian Splatting to assist learners in imitating correct movements. Through close collaboration with a Tai Chi coach and demonstrative sessions, we iteratively refined our system and

doi:10.6342/NTU202503584

observed its potential to support both skill development and self-awareness. While this study focuses on qualitative feedback, future work will involve formal user studies and hardware refinement. Ultimately, our system provides a novel approach to making the invisible principles of internal martial arts perceptible, measurable, and teachable through immersive technology.

Keywords: Tai Chi Pushing Hands, Visual Feedback, Extended Reality, Wearable Sensing Technology, Embodied Learning

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Chapter 1　Introduction

Tai Chi is a traditional Chinese martial art with origins dating back to 13th-century China, during the transition between the Yuan and Ming dynasties. It is well-established that Tai Chi offers significant health benefits, particularly in relation to physical fitness [5]. As a result, a growing number of people around the world now practice Tai Chi as a form of exercise. With this increasing popularity, researchers have begun to explore the use of extended reality (XR) technologies to enhance the way people learn and practice Tai Chi.

Tai Chi pushing hands is a partnered exercise derived from traditional Tai Chi forms. This practice trains practitioners to respond to and neutralize an opponent's pressure while maintaining balance. It also emphasizes the Yin-Yang principle, where partners alternate between the roles of attacker (Yang) and defender (Yin) to achieve harmony. A central skill in pushing hands is Tīng Jìng (聽勁)—the ability to sense or “listen to” an opponent's intentions. Mastery of Tīng Jìng is considered crucial for both casual practice and competitive settings. The heightened sensitivity developed through Tīng Jìng can even translate to improved awareness and responsiveness in daily life. Despite its importance, Tīng Jìng is typically taught only through personal instruction from an experienced Tai Chi coach. Mastering this skill requires an understanding of subtle Taoist concepts underlying Tai Chi, which can be challenging for beginners. Currently, there are no tools or

doi:10.6342/NTU202503584

systems available to objectively quantify a practitioner’s performance in pushing hands, making progress in Tīng Jìng difficult to measure.

To address these challenges, we are developing an XR-based training system for Tai Chi pushing hands. When two individuals practice pushing hands, their hands remain in contact, creating a pressure point that can be measured using sensors. Our system utilizes a wearable sleeve embedded with pressure sensors and a microcontroller to collect pressure data from the point of contact and transmit it to XR headsets in real time. Within the XR headset, users are guided by a virtual coach that performs pushing hands movements, while a visual interface provides real-time feedback on the applied pressure. Research suggests that immediate visual feedback during training can enhance motor skill acquisition; thus, incorporating visual feedback training (VFT) into Tai Chi pushing hands practice may facilitate more effective and engaging learning experiences.

doi:10.6342/NTU202503584

Chapter 2 Related Works

With the accessibility of extended reality (XR) headsets, various XR applications and studies have been conducted to enhance users' ability to learn different skills. These XR applications primarily provide animations, visual cues, and feedback for users to follow, aiming to improve their performance in specific skills. Yu Qing et al. [30] conducted a brief survey exploring various feedback techniques for martial arts learning in VR. Most of the works reviewed showed positive improvements for users after utilizing such systems. Although this study focused on VR applications, the underlying concepts and techniques can be extended and integrated into broader XR applications.

2.1 XR Martial Arts Learning

Conventional XR-based martial arts learning systems typically present specific movement forms for users to follow or imitate. For example, Okada et al. [22] proposed a Tai Chi–based physical therapy game in which users imitate a virtual avatar's movements and are scored based on how accurately their performance matches the avatar's motions. However, because this system relied on a conventional flat-screen display, it inherently limited user movement; performing Tai Chi forms often requires turning around, which is difficult when one must always face a fixed screen.

To overcome such limitations, Han et al. [12] developed My Tai-Chi Coaches, a system leveraging the Microsoft HoloLens (an optical see-through mixed reality headset) to project multiple virtual Tai Chi coaches around the user. Each virtual coach performs Tai Chi routines derived from motion-capture data, providing the practitioner with 360-degree visual guidance. The system also employs a camera drone as an “augmented mirror”: the drone captures the user’s posture and displays it within the AR view, allowing practitioners to observe their own form and directly compare it to the virtual coach’s posture.

Moving beyond animation-based feedback, Suzuki et al. [23] introduced Gino.Aiki, a mixed reality system that uses visual metaphors to guide practitioners in the proper application of force during Aikido training. Kung Fu Metaverse [25] provides users with virtual coaches who demonstrate specific Kung Fu movements in various virtual environments, including both passthrough mode and fully immersive VR. During practice sessions, the system delivers visual feedback—such as color changes on movement trails based on users’ hand movements—enabling real-time correction and enhanced motor learning. Tian et al. [24] incorporated social presence in their XR Tai Chi training system, enabling users to see each others’ hand movement trajectories during training sessions. This makes it easier for Tai Chi coaches to demonstrate certain movements or observe students’ performance, providing them with guidance and feedback.

Overall, displaying visual guidance in the form of a virtual coach or visual cues can assist users in learning martial arts more effectively. In Tai Chi pushing hands, beyond simply following movements from a coach, another critical aspect is the ability to perceive and respond to the pressure exerted by oneself and one’s partner while maintaining balance. In this work, we aim to integrate pressure visualization in addition to providing a virtual coach, to guide users in learning Tai Chi pushing hands.

doi:10.6342/NTU202503584

2.2 Force Data Acquisition for XR Applications

To visualize the force exerted by users within XR headsets, it is first necessary to acquire relevant force data using appropriate devices and transmit it to the XR system. One widely recognized consumer device for measuring pressure or force is the Wii Balance Board [6], which tracks a user’s center of balance and utilizes this information in the game Wii Fit. Similarly, Ishac et al. [10][17] developed an IoT pressure-sensing mat that captures pressure data and provides users with visual feedback during remote martial arts training.

While these previous works have focused on standalone devices, other approaches have explored wearable solutions that are easier to deploy. For example, Kao et al. [19] employed pressure-sensing insoles to detect weight distribution in Tai Chi practitioners, helping users maintain correct posture through proper weight allocation. Likewise, Jan et al. [18] integrated pressure-sensing insoles with camera data, enabling a scoring system that allows users to review their poses using Microsoft HoloLens. Additionally, Zhang et al. [31] utilized electromyography (EMG) sensors to collect force data and visualize it through objects with physical properties in XR environments. However, while EMG sensors provide an easy-to-use wearable solution, they only detect the force output of the wearer’s own muscles, making them unsuitable for pushing hands, which requires continuous hand contact between two participants.

Upon reviewing these works, it is evident that utilizing pressure sensors at the points of contact between pushing hands practitioners offers a more feasible solution for accurately capturing and visualizing the pressure involved in XR-based training.

2.3 Visual Feedback Training in XR

In addition to employing virtual coaches in extended reality (XR) training, another effective strategy for enhancing skill acquisition is visual feedback training (VFT). VFT involves capturing real-time performance data—such as motion, force, or balance metrics—via sensors, and instantly displaying this information to the user during training. This immediate feedback allows users to observe their own performance and make timely adjustments for improvement.

For example, Hohmuth et al. [13] developed the Wireless Rowing Measurement System (WiRMS), which collects a rower’s motion and muscle activity data and streams it in real time to a tablet on the boat, providing athletes with immediate feedback on their technique. Similarly, Vando et al.[26][27] demonstrated that providing visual feedback on balance can improve martial artists’ stability. In thier study, young karate athletes trained on a Wii Balance Board with real-time visualization of their center-of-pressure (COP), and showed significant improvements in postural control compared to a no-feedback group. In subsequent work, pressure-sensing insoles were used to visualize COP data for karate practitioners, also yielding positive effects on balance and motor control. Notably, these studies delivered feedback through standard 2D displays, such as tablets or monitors, which—while effective—can limit the user’s field of view and sense of immersion.

Recent projects have leveraged XR technologies to present feedback more immersively, thereby expanding the user’s perspective and engagement. Hülsmann et al. [15] utilized a motion-capture system and machine learning to analyze users’ movements (such as squats and Tai Chi pushes), and automatically generated corrective feedback in real time. Feedback was presented as augmented visual cues (e.g., colored highlights) on the user's avatar, observable within a CAVE (Cave Automatic Virtual Environment) immersive display. Likewise, Najami and Ghannam [21] developed a VR-based tennis training system that provides real-time swing analytics to the player. In their system, a wearable sensor on the player's racket hand captures swing speed and power, and the data are visualized instantly as overlays in the VR headset. Novice tennis players who trained with this immediate visual feedback showed improvements in swing consistency and situational awareness, and reported greater engagement and motivation due to the immersive experience.

These examples illustrate how integrating VFT with XR can significantly enrich the learning experience, providing users with a real-time, first-person perspective on their performance and guiding them toward improved technique in a more engaging and effective manner.

doi:10.6342/NTU202503584

Chapter 3 Design Considerations

3.1 Collaboration with Tai Chi Practitioners

Inspired by the use of first-person perspective in soma-based design proposed by Höök et al.[14], we chose to gain firsthand experience with Tai Chi pushing hands prior to beginning system development. To this end, we enrolled in four basic Tai Chi pushing hands sessions to learn both the core movements and practice routines. During these sessions, the coach focused on teaching key movements (as illustrated in Figure3.1) and stances, while providing real-time corrections to our form. As we progressed, the coach encouraged us to pay close attention to the subtle pressure exchanged during practice.

Figure 3.1: Pushing hands routine: (a) Starting stance, (b) attacker on the right begins to push while the defender on the left starts to yield, (c) defender diverting the ”attack”.

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Through this immersive process, we began to understand the concept of Tīng Jìng , which requires active collaboration between practitioners. For example, when the attacker initiates a push, the defender must yield by stepping back (see Figure 3.1b), then apply a subtle force to the attacker’s elbow and wrist to divert the push (see Figure 3.1c). The roles of attacker and defender then alternate.

These firsthand experiences led us to recognize that Tīng Jìng could potentially be quantified by using pressure sensors to measure the pressure exchanged during pushing hands practice. We drew further inspiration from Bang et al. [9], who engaged the Duncan dance community in co-designing sounding scarves for dancers, ensuring effective system integration in real-world contexts. Following our initial sessions, we continued to participate in the community’ s weekly Tai Chi pushing hands practices, discussing system needs and design improvements with the coach. This ongoing collaboration enabled us to gain deeper insights into user requirements and iteratively refine our system.

3.2 Modular Design for Pressure Data Acquisition System

In Tai Chi pushing hands, two practitioners maintain contact by placing their hands together—a technique known as “Da Shou” (搭手). The most common contact points are the elbow and the back of the hand (see Figure 3.2). From this stance，the practioners will learn the simplest movement called “Flat Push (平推)” where they have to push and yield. Practitioners are also guided by the principles of “not releasing” (不丟) and “not resisting” (不頂), which are essential for maintaining the internal balance of “Yin and Yang” [8]. We propose measuring the pressure at these two contact points to provide an

doi:10.6342/NTU202503584

objective reference for users to evaluate their adherence to these foundational principles.

Figure 3.2: Contact points for Da Shou in Tai Chi pushing hands

To measure the pressure, we employ force-sensitive resistors (FSRs) positioned on wearable sleeves. Since arm lengths vary among individuals, we designed a modular sensor placement system to maximize adaptability. In the ThermoTouch project [28], the authors implemented a modular design by separating the main board from the haptic module, connecting them with conductive yarns. Following a similar strategy, we separate the sensors and microcontroller, connecting them via modular connectors. This allows sensors to be positioned appropriately for each user.

Based on our personal experience with Tai Chi pushing hands and further consultation with our Tai Chi coach, we decided to add two additional sensors at key contact points—the wrist and the front part of the forearm—to improve pressure visualization during the "sticking and adhering method" (黏貼法). This brings the total number of contact points to four, as illustrated in Figure 3.3. The visualization in Figure 3.3 displays the contact points for both practitioners, corresponding to the actual sensor placement locations.

Drawing further inspiration from Kollanur et al. [20], who used tiles and straps to position haptic actuators on users' arms, we chose hook-and-loop fasteners (Velcro) to

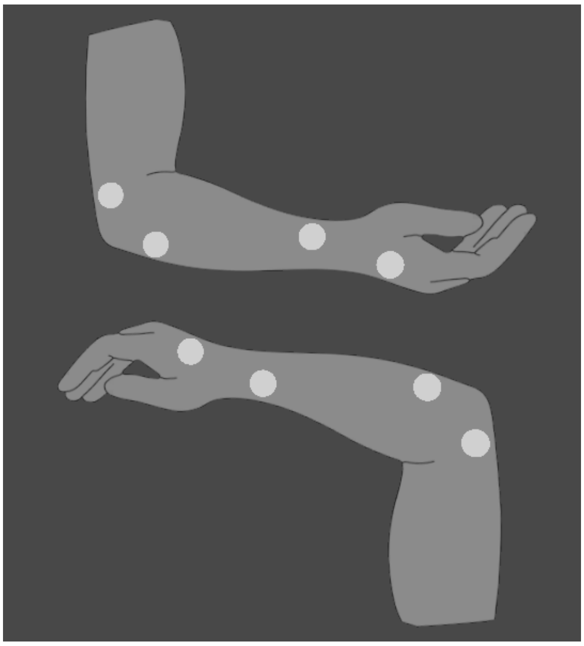

Figure 3.3: Contact points for both practitioners during the sticking and adhering method.

affix the sensors to the wearable sleeves. As FSRs require a stable, unbent surface for accurate measurement, we constructed a wide band from loop fastener material; sensors with hook fasteners can be attached anywhere along the band for flexible placement. For added comfort, users wear a sports sleeve underneath the sensor band.

3.3 Visualization Interface Design

3.3.1 Virtual Coach

Previous research suggests that a virtual coach demonstrating specific movements can assist users in acquiring targeted skills within XR environments. Building on this insight, we sought to incorporate a similar element into our system. The virtual coach in our system also serves as a guide to help users improve their skills. The speed at which the virtual coach performs the routine can be adjusted. When the speed is slow, users can push slowly, making it easier to control the pressure exerted. However, when the virtual

doi:10.6342/NTU202503584

coach performs the routine at a faster pace, users must match the speed while maintaining appropriate pressure. This helps deepen their understanding and practice of Tīng Jìng.

Most martial arts learning platforms utilize motion capture (MoCap) technology to record the movements of expert coaches and retarget them to 3D avatars. While this method offers flexibility in adjusting and reusing recorded motions, it poses significant challenges when applied to Tai Chi Pushing Hands.

Firstly, Pushing Hands is a two-person practice that involves close physical proximity. In such scenarios, the raw MoCap data often requires extensive post-processing to correct artifacts. Otherwise, mesh interpenetration—a common issue where body parts or avatars unrealistically intersect—can occur. Additionally, the continuous forearm and hand contact intrinsic to Tai Chi Pushing Hands increases the likelihood of occlusion, where tracking markers become blocked from view, leading to inaccuracies or drift in the avatar's motion.

To address these limitations, we explored 4D Gaussian Splatting [29] as a more cost-effective and robust alternative for capturing and presenting the coach's movements. This method uses multiple consumer-grade cameras—such as smartphones or webcams—to generate photorealistic, volumetric renderings without the need for specialized suits or marker-based setups. Compared to traditional MoCap, this approach significantly reduces hardware and operational costs while minimizing setup complexity and intrusiveness for users. More importantly, Gaussian Splatting is inherently more resilient to occlusion and close-contact interaction, making it well-suited for preserving the fluid and subtle movements characteristic of Tai Chi Pushing Hands.

Moreover, Gaussian Splatting provides superior visual fidelity compared to conven-

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tional 3D avatars, as it directly reconstructs the subject's appearance from real images. As illustrated in Figure 3.4(a) shows the coach captured using Gaussian Splatting, while Figure 3.4(b) presents motion retargeted to a 3D avatar. The differences in realism and detail further highlight the benefits of this approach for immersive learning applications.

Figure 3.4: Virtual coaches: a) Gaussian Splatting, b) 3D avatar driven by motion capture data.

3.3.2 Plot Design

Tai Chi pushing hands practice involves two practitioners, with one acting as the ”attacker” (Yang) and the other as the ”defender” (Yin), with roles alternating throughout the routine. To visualize the pressure data generated during these interactions, we employed time-varying plot to clearly represent performance trends.

In designing the visualization interface, we referenced the design space for glanceable feedback proposed by Gouveia et al. [11]. Specifically, we drew insights from their discussion of “time windows”: short windows (e.g., five seconds) are useful for reac-

doi:10.6342/NTU202503584

tion training, while longer windows (e.g., two minutes) provide a broader overview of performance. While Gouveia et al.'s original work targeted small displays (such as smartwatches), which made it challenging to display both windows simultaneously, our system leverages the larger XR display to present two time-varying plot concurrently—one for a five-second window and one for a two minutes window. The short-window plot allows users to focus on immediate pressure application, while the long-window plot supports review of overall performance throughout the routine.

To facilitate rapid interpretation, we prioritized simplicity and adopted color coding: green (appropriate pressure), yellow (alert zone), and red (excessive or insufficient pressure), following recommendations for minimizing cognitive load.

3.3.3 Visualization Interface Spatial Placement

The spatial placement of the data visualization interface in the XR headset was carefully considered to accommodate the varying head movements required by different Tai Chi pushing hands routines. According to the Human Interface Guidelines for interaction zones in AR [32], the optimal viewing angle for content is within ±15 degrees of the user's line of sight. We therefore positioned the visualization interface within this comfortable viewing zone. Additionally, the placement of the virtual coach also stay within the viewing angle mentioned above which can be shown in Figure 3.5. The placement of the coach was inspired by how we follow the pushing hands routine during our Tai Chi class. The coach typically stands at either the front right or front left while we practice the routine.

For routines that do not require head movement, the visualization interface remains static (world-locked). For routines involving head turning, the interface is loosely attached

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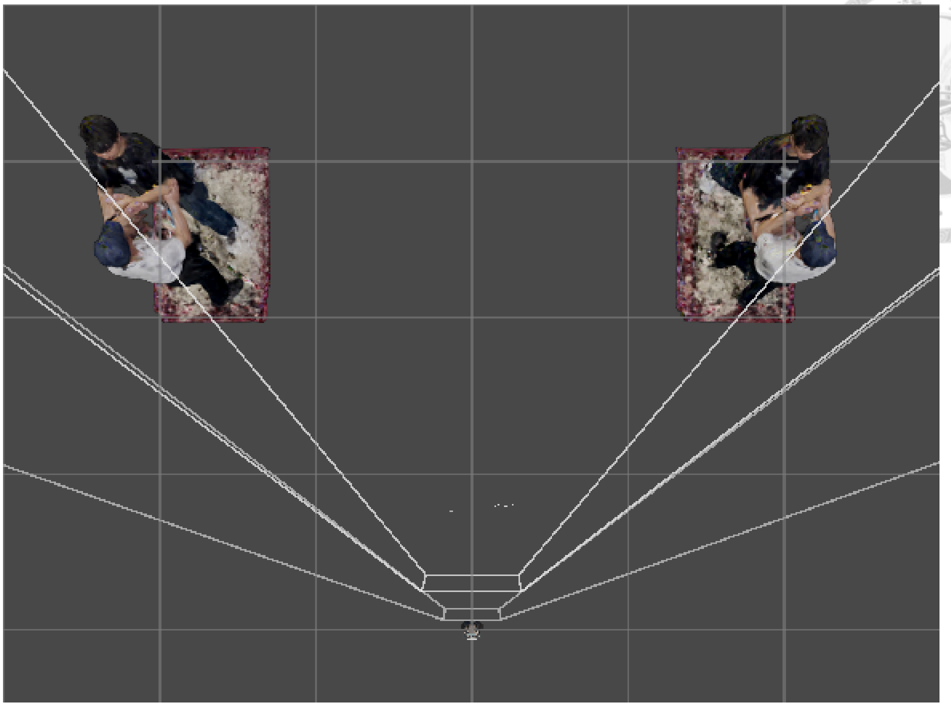

Figure 3.5: Top view of the placement of virtual coach in XR headset.

to the user's head movement, in accordance with mixed reality design guidelines provided by Meta [3].

Chapter 4 Design and Implementation

After experiencing Tai Chi pushing hands and gaining an understanding of its core concepts, we developed a visual feedback training system specifically for Tai Chi pushing hands. Our system consists of two main components: wearable sleeves with integrated pressure sensors and XR content displayed on the Meta Quest 3 headset. The system utilizes Wi-Fi to transmit data from the microcontroller to the Meta Quest 3 headset.

4.1 Wearable Sleeves for Data Acquisition

The current prototype of the wearable sleeve is constructed using a commercially available sports sleeve combined with hook-and-loop fasteners, as shown in Figure 4.1. The top sleeve in the figure represents our modified version, while the bottom sleeve shows the original sports sleeve.

Figure 4.1: Wearable sleeve: (top) modified version, (bottom) original sports sleeve

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For data acquisition, we selected the ESP32 microcontroller [1], which provides both Wi-Fi connectivity and analog signal reading capabilities suitable for our application. The force-sensitive resistors (FSRs) used are the FSR-406 model [16]. Each FSR-406 is connected to the microcontroller via a 10kΩ resistor, enabling the measurement of applied pressure. The entire circuit is powered by a rechargeable lithium battery. The connection details are illustrated in Figure 4.2.

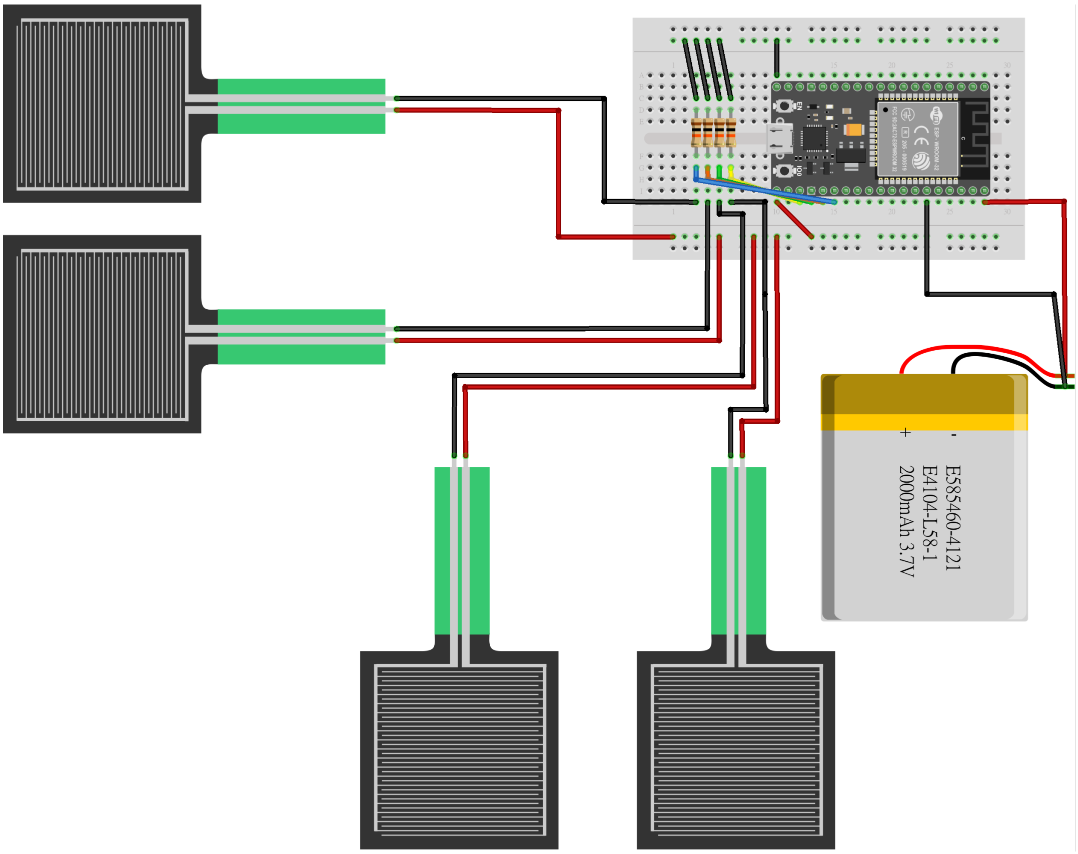

Figure 4.2: System circuit for data acquisition

After assembling the circuit, the pressure sensors are calibrated using known weights of 10,g, 20,g, 50,g, and 100,g. Real-time data collected from the sensors is transmitted via Wi-Fi to the Meta Quest 3 headset using the Open Sound Control (OSC) protocol [4], which is straightforward to implement and does not require an additional server. The complete prototype of the wearable sleeve for data acquisition is shown in Figure 4.3.

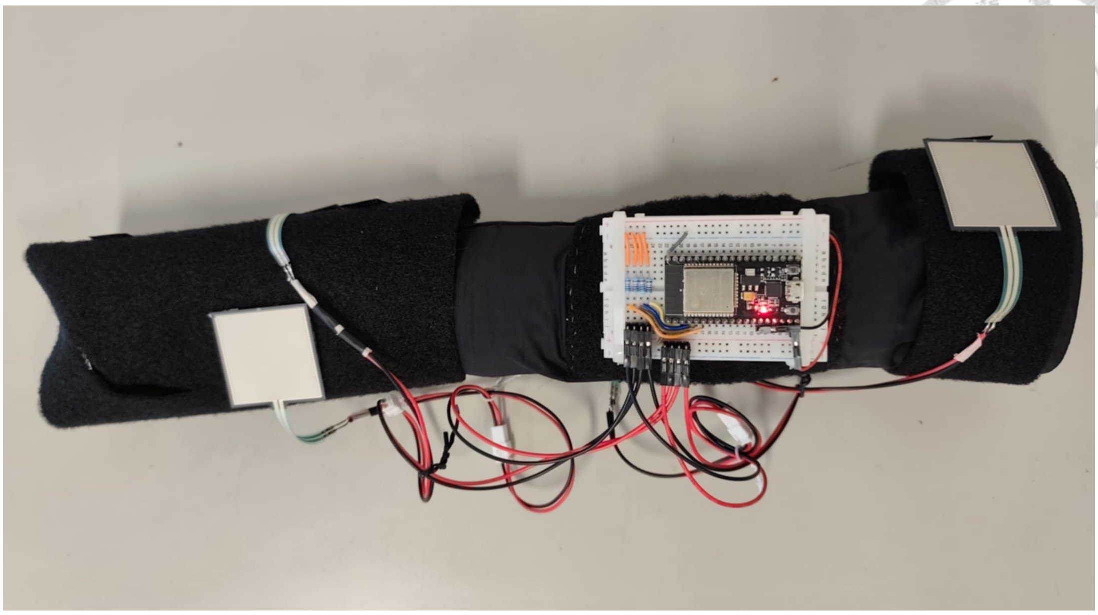

Figure 4.3: Prototype of the wearable sleeve for data acquisition

4.2 Visual Feedback Training Interface in XR Headset

4.2.1 Learning Component

As discussed in the related works, a virtual coach can assist users in learning martial arts by providing reference movements for imitation. Traditionally, virtual coaches in previous studies have relied on motion capture technologies to record Tai Chi coaches' movements and retarget them to virtual avatars. In our work, we implement the virtual coach using the state-of-the-art 4D Gaussian Splatting method to capture Tai Chi pushing hands movements. This approach enables photorealistic rendering and eliminates the need for tracker suits, which might hinder the natural movement during Tai Chi pushing hands practice.

We captured the pushing hands movements (as shown in Figure 4.4) using eleven iPhone 12 and twelve iPhone 12 Pro cameras, then processed the data with the method proposed by Wang et al.[29].

doi:10.6342/NTU202503584

Figure 4.4: Environment of Gaussian Splatting capturing session

To render the Gaussian Splats assets on Meta Quest 3, we utilized the Unity package published by Aras Pranckevičius[2]. We used Unity 6 and Meta XR All-in-One SDK to set up the passthrough environment and overlay the Gaussian Splats on top of it. The outcome can be seen in Figure 4.5. After that, we will built the application as an APK file for installation on the XR headset.

Figure 4.5: Virtual Coach in XR environment, screenshot from Meta Quest 3

doi:10.6342/NTU202503584

4.2.2 Visual Feedback Component

The visual feedback component, implemented as a time-varying plot visualization, is built using the Line Renderer and panels within the Unity game engine. This component receives real-time data from the microcontroller on the wearable sleeves via the OSC protocol. The data range from 0 to 100g, where 0g indicates no contact between users, and 100g indicates over-resisting. These two values suggests that the users are not following the principles of pushing hands, particularly those of sticking and adhering during the practice. The users will have to maintain the pressure value between this two values in order to perceive Tīng Jìng. The panels displaying the plot are color-coded as described in the design considerations. To enhance environmental awareness, the panels are designed to be translucent, ensuring they do not fully obstruct the user's view of their opponent's movements. This component is rendered as an overlay on top the passthrough layer of the Meta Quest 3, allowing real-time data to remain visible at all times. The above description can be seen in Figure 4.6.

Figure 4.6: Visualization Interface Design on XR headset

Additionally, to improve users' understanding of where pressure is being applied on the forearms, we provide a forearm illustration corresponding to the actual sensor placement on the user's arm. For example, when pressure is applied to the wrist, the circle at the wrist area in the illustration changes color, and the pressure in grams is displayed next to it, as shown in Figure 4.7. This component reflects instantaneous changes in pressure, while the time-varying plot visualization depicts pressure changes over time.

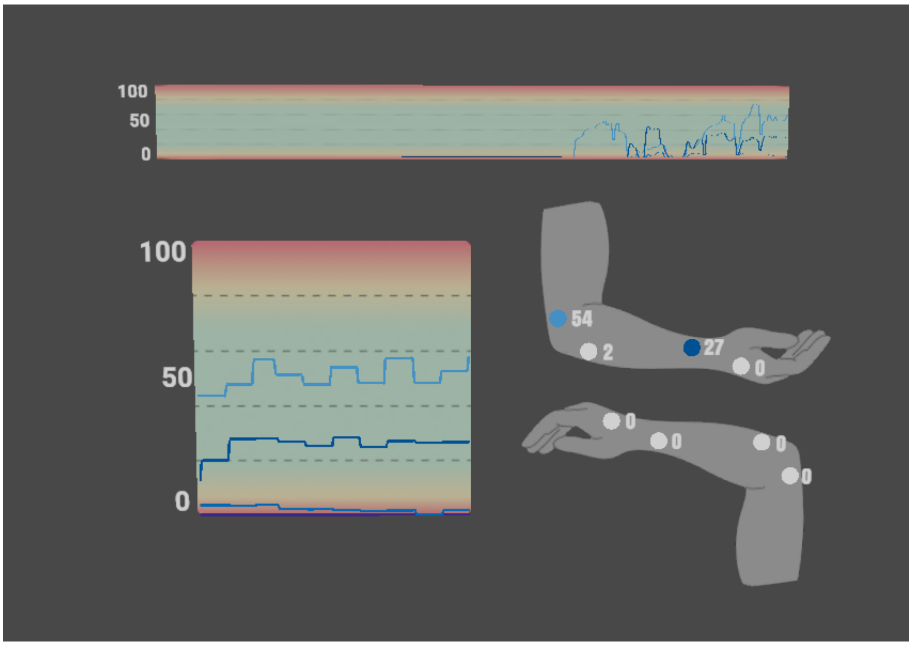

Figure 4.7: Visualization Interface Design: Top, longer time window; Bottom left, shorter time window; Bottom right, mapped sensor locations on the forearm.

Chapter 5 User Scenario and Discussion

5.1 Demonstrative Scenarios

To validate our system design, we conducted a demonstration with our Tai Chi pushing hands coach. Our Tai Chi coach is Master Wu Rong-Huei, who also serves as the Vice Chairman of the National Tai Chi Chuan Association (Taiwan) and the World Tai Chi Chuan Federation. Master Wu holds a master's degree in coaching science from National Taiwan Sport University and authored a thesis titled Traditional Tai Chi Chuan and Push-Hands[33], which forms part of the foundation of our learning experience in his class. He trained under Grandmaster Song Zhi-Jian, who is in the direct lineage of Cheng Man-Ching and Yang Cheng-Fu. With over 30 years of experience in teaching and competing in Tai Chi Pushing Hands, he has also served as a coach and head referee in numerous national and international tournaments [7].

We brought our prototype to a training session and introduced it to the coach. As shown in Figure 5.1, the coach wore both our prototype and the Meta Quest 3 headset during pushing hands practice. Because our system is designed to help users understand Tīng Jìng (聽勁) by visualizing the applied pressure, both participants were required to wear the headset as shown in Figure 5.1. This setup enabled both users to perceive the pressure, specifically, how much pressure to apply or release—during their interactions.

doi:10.6342/NTU202503584

During the initial demonstration, the pressure sensors recorded values ranging from 0 to 500g based on our first calibration. However, we observed that the pressure actually applied by the coach was much lighter, typically between 25 and 75g. Upon further consultation, the coach explained that proper pushing hands practice requires gentle pressure to develop the concept of Tīng Jìng.

Initially, our visual feedback interface consisted only of time-varying plot displaying the overall pressure. The coach suggested that it would be more useful to also display real-time pressure values applied to different parts of the arm. Based on this feedback, we refined our visualization interface to include this functionality, as shown in Figure 4.7.

Figure 5.1: Tai Chi coach using our system with one of the students.

Additionally, the coach expressed appreciation for the virtual coach implemented using Gaussian Splatting and recognized its potential for remote instruction. From our perspective, the use of Gaussian Splatting significantly enhances the visual experience by providing photorealistic renderings of the coach. Compared to motion-captured data retargeted onto a 3D avatar, this approach fosters a stronger sense of presence and connection between users and the coach.

5.2 Effectiveness of Our System

The demonstrative session held in the Tai Chi class, along with our ongoing collaboration with the Tai Chi coach, provided valuable qualitative insights into the potential and effectiveness of our system.

Our classmates expressed excitement and interest in the system, particularly as they observed their subtle pressure applied to the sensors reflected immediately in the XR headset's visualization interface. The time-varying plot offered real-time cues on the amount of pressure being applied during pushing hands, enhancing both practitioners' awareness of subtle pressure transitions.

Based on our experience in attending Tai Chi pushing hands classes, we noted that the typical learning process begins with observing the coach to learn stances and movements, followed by imitation. Only after mastering the basic movements do practitioners focus on the appropriate amount of pressure to apply and on techniques for yielding or releasing pressure. Our system addresses these stages by first providing a virtual coach to help users learn movements without time or space constraints. As users progress, the wearable sleeves integrated with pressure sensors and the visualization interface are introduced, helping them understand the concept of Tīng Jìng and improve their abilities in pushing hands.

The coach observed that beginners often struggle to recognize when they are overex-

doi:10.6342/NTU202503584

erting or resisting unnecessarily. The visualization interface helped reveal these behaviors, especially when the applied pressure exceeded expected thresholds. For example, the real-time display of pressure entering the red zone provided immediate feedback, prompting users to adjust their posture or hand pressure accordingly. This observation aligns with prior research indicating that visual feedback can enhance motor learning by providing immediate sensory cues [13, 27].

Additionally, the system’ s visual feedback enabled after-action review. Practitioners could review session data to observe the overall pressure distribution over time, supporting the internalization of the Tīng Jìng principle.

5.3 Limitations

We presented a system that measures the pressure applied by users during Tai Chi pushing hands and visualizes it in XR headsets to assist with learning Tīng Jìng. However, the system has several limitations. Tai Chi pushing hands involves more than just the two movements— “Flat Push” and “Sticking and Adhering Method” —addressed in this work. Other movements, such as “Outer Forearm Contact” (外層接), “Inner Forearm Contact” (內層接), and “Four Direction Pushing Hands” (四正推手), require additional sensors to be attached to the user’s upper forearm and shoulders, which our current prototype does not support.

Another hardware limitation is that the microcontroller circuit would need to be further customized, as the ESP32 allows only six analog-to-digital converter (ADC) pins to function simultaneously when the Wi-Fi feature is enabled. For future integration into Tai Chi pushing hands training, a redesigned PCB would be necessary to reduce the bulkiness

doi:10.6342/NTU202503584

of the current prototype and make it more comfortable and practical for users to wear.

In addition, the current system utilizes multiple individual FSR-406 sensors. Due to the characteristics of these sensors, each one must be calibrated individually after a certain period of use, which would require the support of a technician if the system were to be deployed more broadly in Tai Chi Pushing Hands practice sessions. Through our survey, we found that while commercially manufactured pressure-sensing insoles are available, similarly customizable sensors designed for wearable sleeves are not. If such sensors were available, our system would be significantly easier to set up and operate compared to the current prototype.

5.4 Reflection on Our System

Tai Chi Pushing Hands is based on traditional Chinese martial arts principles that focus on internal awareness, subtle touch, and learning through physical interaction rather than verbal explanation. One important skill, Tīng Jìng, is often taught through long-term practice and is hard to explain or measure with modern tools. By adding real-time visual feedback and pressure sensing, our system may raises a question: can technology support such an internal skill without oversimplifying it?

Our goal is not to replace traditional instruction or change the meaning of Tīng Jìng. Instead, we aim to help beginners who are still developing their sensitivity. For them, the system works like training wheels —it shows when they apply too much force or resist when they should yield. Over time, as learners improve, the system can be used less or turned off entirely, allowing them to rely more on their own sense of touch.

Balancing tradition and technology is a key idea in our design. We understand that not everything in Tai Chi can or should be digitized. Our approach is to use XR to support the learning process in a respectful way, without replacing the original spirit of the practice.

Chapter 6　Conclusion

In this paper, we presented a system that measures the pressure exerted by users during Tai Chi pushing hands and visualizes it in XR headsets to enhance practitioners’ ability to perceive Tīng Jìng (聽勁). Our system also integrates a virtual coach rendered using Gaussian Splatting, enabling learners to observe and imitate realistic Tai Chi movements as part of their training.

By actively engaging in Tai Chi pushing hands practice and collaborating closely with a professional Tai Chi coach, we refined both our system and design approach to better align with the needs and values of real-world practitioners. This collaboration provided valuable qualitative insights, especially in understanding how subtle pressure interactions are perceived, practiced, and taught.

The key contributions of this work include:

1. A modular wearable sleeve system capable of collecting and transmitting pressure data during live Tai Chi practice.

2. A visual feedback interface in XR that offers both real-time and reflective feedback to support users’ motor learning and internalization of Tīng Jìng.

3. The integration of a photorealistic virtual coach using Gaussian Splatting, offering

an immersive learning experience without the need for complex motion capture setups.

For future work, we plan to conduct formal user studies with both Tai Chi learners and instructors to evaluate learning outcomes and gather feedback on system usability. We will also explore variations in interface design, time window settings, and alternative methods such as Structure from Motion, to further refine our approach and validate the choice of Gaussian Splatting and XR integration. We also plan to enhance the hardware by developing custom printed circuit boards (PCBs) to improve the system's compactness, structural stability, and user comfort. A distributed multi-microcontroller architecture will be considered to minimize the length of sensor connections, thereby reducing potential interference with user movement and improving overall wearability. Furthermore, integrating pressure-sensing insoles could allow users to visualize their center of pressure along with hand-based pressure data, offering a more holistic view of balance and technique.

By combining traditional martial arts wisdom with emerging XR technologies, this work illustrates how cultural practices can be enhanced by digital innovation. Our system serves as a blueprint for future explorations of how designers and engineers can collaborate with embodied practice experts, such as Tai Chi Pushing Hands coaches, to integrate traditional movement knowledge into XR technologies.

doi:10.6342/NTU202503584

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