EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY

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DECEMBER 2024

OOI XIN ROU EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY 2024

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By

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A Research Project submitted to the Department of Physiotherapy,

M. Kandiah Faculty of Medicine and Health Sciences,

Universiti Tunku Abdul Rahman,

in partial fulfillment of the requirements for the Degree of Bachelor of Physiotherapy (Honours)

20th December 2024

EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY

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ABSTRACT

Background and Objective: Postural control is crucial for stability and fall prevention. However, traditional clinical methods are often subjective, exhibit examiner's biases and lack sensitivity. Recent sensor-based technologies offer objective measurements but are costly, less portable, and require space and complex setups. This study explores a novel system with six lightweight sensors strategically placed on anatomical landmarks to detect postural changes. The objectives of this study were: (1) analyzing the measurement accuracy of the sensor system in capturing and quantifying real-time postural changes, (2) evaluating the intra-session reliability of the sensors in detecting postural changes over repeated trials, and (3) determining the concurrent validity of the sensor system against the gold standard MDRT.

Methods: 58 participants were recruited for this study through face-to-face and social media. After screening for eligibility, participants performed the MDRT while the sensor system simultaneously recorded postural changes. Sensor data on reach distances were processed using Blender; while MDRT data on reach distances were collected manually.

Results: The key findings were: (1) the sensor system does not accurately capture and quantify real-time postural changes (2) there is significant intra-session reliability of the sensors in detecting postural changes over repeated trials (ICC>0.6, p<0.001) and (3) there is no significant correlation between the postural change measurements from the sensor system and MDRT, as FR (r_s= -0.307, p=0.020) and LR (r_s= -0.285, p=0.031) show significantly poor negative correlations; while BR (r_s= -0.145, p=0.281) and RR ($r_{s=}$ -0.052, p=0.702) show no correlations. Thus, the overall relationship is not strong enough to support the alternate hypothesis.

Conclusion: The current study shows the sensor system lacked accuracy detecting postural reactions. While offering a cost-effective and portable solution, improvements in sensor sensitivity, calibration, and connectivity are needed. Future research should focus on refining the system and conducting longitudinal studies to enhance its applicability across diverse populations.

Keywords: Sensor system, Postural Reactions, Pilot study

ACKNOWLEDGEMENTS

I would like to express my heartfelt appreciation to all those who contributed to the success of this research project. First and foremost, I deeply appreciate all the participants who generously engaged in this research study. This research project would not have been possible without their willingness to engage. I am genuinely grateful for their time and cooperation.

I am deeply grateful to my supervisor, Dr. Deepak Thazhakkattu Vasu, for his exceptional guidance and support throughout the entire final year project period from the proposal stage to completion. His guidance during every meeting helped me clear my research progress and also helped me navigate challenges with confidence.

Furthermore, I wish to express my appreciation to UTAR for providing the necessary resources and a conducive space at the physiotherapy center. The facilities and support staff enabled me to conduct the research project effectively.

Additionally, I am especially thankful to my esteemed UTAR senior Ms. Tammy for her invaluable guidance and mentorship during various phases of this research project. Her support was essential in facilitating this work.

Finally, a special thanks goes to my friends and family for their unwavering support and understanding throughout this journey. Their belief in my abilities kept me motivated and their encouragement has meant so much to me.

APPROVAL SHEET

This Research project entitled "**EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY**" was prepared by OOI XIN ROU and submitted as partial fulfillment of the requirements for the degree of Bachelor of Physiotherapy (Honours) at Universiti Tunku Abdul Rahman.

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Date: 18th December 2024

PERMISSION SHEET

It is hereby certified that OOI XIN ROU (ID No: 22UMB00080) has completed this Research project entitled "EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY" under the supervision of DR. DEEPAK THAZHAKKATTU VASU (Supervisor) from the Department of Physiotherapy, M Kandiah Faculty of Medicine and Health sciences.

I hereby give permission to the University to upload a softcopy of my final year project in PDF format into the UTAR Institutional Repository, which may be made accessible to the UTAR community and the public.

Yours truly,

(OOI XIN ROU)

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DECLARATION

I hereby declare that the Research project is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Name: OOI XIN ROU

Date: 18th December 2024

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Abbreviations	
MDRT	Multidirectional Reach Test
UTAR	Universiti Tunku Abdul Rahman
COM	Centre of Mass
LOS	Limits of Stability
FRT	Functional Reach Test
M	Mean
SD	Standard Deviation
α	Cronbach’s Alpha
ICC	Intraclass Correlation Coefficient
r_s	Spearman's Rank Correlation Coefficient
FR	Forward Reach
BR	Backward Reach
LR	Left Reach
RR	Right Reach

CHAPTER 1

INTRODUCTION

1.1 Chapter Overview

This chapter will provide an overview of the study's background, including the problem statement and research question. It will also cover the aims, objectives and hypotheses of the study. Following this, the operational definitions of the key terms for the study will be presented, along with a discussion of the rationale and scope of the study.

1.2 Background of Study

Postural control is an essential skill that enables individuals to maintain stability and orientation, thereby facilitating the performance of activities of daily living. This complex system involves intricate interactions between sensory and motor functions (Mancini et al., 2020). The vestibular system, visual system and proprioceptors are the key sensory systems involved in posture control. The central nervous system integrates these systems to maintain equilibrium in response to perturbations (Nashner & McCollum, 1985). Additionally, ankle and hip techniques are also crucial for maintaining postural stability (Nashner & McCollum, 1985). Understanding these mechanisms is essential for developing effective interventions to improve balance and prevent falls in various populations.

Recent research has significantly advanced our understanding of the mechanisms underlying postural control, particularly through studies delineating its dual functions: postural stability and postural orientation (Suellen et al., 2024). Postural stability involves managing the center of mass (COM) in relation to the base of support, particularly against gravitational forces. In contrast, postural orientation refers to aligning body segments with one another and with the surrounding environment to facilitate effective perception and action (Suellen et al., 2024).

As individuals age, postural control mechanisms undergo significant changes, often leading to increased instability and a heightened risk of falls. Older adults frequently exhibit impaired postural control due to age-related sensory declines (Patti et al., 2023) or more reliance on the hip strategy (Appeadu & Bordoni, 2023). Consequently, these changes necessitate a deeper understanding of the postural control system to create effective rehabilitation protocols in balance assessments and fall risk prevention.

Balance assessments that evaluate postural sway and limits of stability (LOS), can help identify fall risks and guide rehabilitation strategies (Degani et al., 2017). However, understanding the mechanism underlying postural control and the necessity for valid and reliable assessment instruments is crucial for forming rehabilitation protocols in balance evaluation and offering insight into preventing fall risks (Paillard & Noé, 2015).

Postural control or balance can be assessed using either traditional clinical tests or sensor-based technologies. Well-known traditional clinical tests such as the Berg Balance Scale (BBS) and Functional Reach Test (FRT) provide valuable insights into an individual's balance capabilities. These traditional tests are widely used in clinical settings due to their cost-effectiveness and ease of setup (Juras et al., 2018). However, recent reviews highlight issues with traditional balance assessments, including examiner's bias, lack of sensitivity to detect minor balance changes and subjectivity (Mancini & Horak, 2010; Chen & Smith, 2019).

Therefore, the recent advancements in sensor technologies provide new avenues for more objective measurement of postural control (Marchesi et al., 2021). These innovations not only enhance our understanding of balance mechanisms but also pave the way for improved rehabilitation strategies tailored to diverse populations. For instance, platform posturography can minimize variability in test performance and remove subjective scoring methods. The reliability of force plates in measuring postural sway is considered good to excellent. However, their utility in community settings is often limited due to their high cost, significant space requirements, and lack of portability (Mancini et al., 2012; Chen et al., 2021).

Several studies have introduced IMU-based posturography that emphasizes the cost-effectiveness and reliability of body-worn accelerometers. For instance, the well-known Vicon motion capture system cooperates with accelerometers to evaluate balance and postural sway across various populations (Kelly et al., 2021). However, Kelly et al. (2021) revealed limitations of this system including impractical for transport uses, difficulty in setup and challenges associated with donning or doffing around external markers (Kelly et al., 2021).

Additionally, the recent HTC Vive motion-tracking system has been employed to evaluate COM displacements and postural stability. While the HTC Vive system is more affordable and user-friendly than the Vicon motion capture system, it faces challenges such as low accuracy and increased latency (Van der Veen et al., 2021). Consequently, it is essential to evaluate sensor-based balance assessment tools not only for their sensitivity and objectivity but also for their convenience, practicality, and usability.

In review, studies have indicated that positioning a sensor on the fifth lumbar vertebra (L5) is advantageous, as it is nearer to the center of mass (Ghislieri et al., 2019). Additionally, sensors located on the lower limbs, such as the shank and thigh, are used to assess postural strategies, while sensors placed on the upper trunk, like those on the sternum, are employed to evaluate trunk tilt (Ghislieri et al., 2019). However, the variability in sensor placement could lead to inconsistencies in measurement outcomes (Kelly et al., 2021).

Additionally, the quantity of sensors used in balance assessments remains inconsistent across studies (Vahid Abdollah et al., 2024). In general, some studies relied on single-sensor systems to detect postural changes. Nevertheless, a multisensor system is essential to capture data from various body areas during postural assessments (Tang et al., 2020). From a usability perspective, it is preferable to use fewer sensors placed on key body landmarks (Pannurat et al., 2017), as multiple sensors can create research challenges due to the complexity and obtrusiveness of the testing equipment (Vahid Abdollah et al., 2024).

A Mocopi sensor system developed by Sony (Sony Corporation - Mocopi | about Mocopi, www.sony.net) shows promise for convenient, portable, affordable and user-friendly sensor system design for real-time motion tracking. It incorporates six inertial measurement unit (IMU) sensors weighing approximately 8g each. This system employs a consistent sensor amount and placement to enhance measurement reliability. The sensors are strategically attached to specific body parts including wrists, ankles, the posterior aspect of the head and the lower back. This anatomical placement ensures optimal accuracy and sensitivity (Kelly et al., 2021). In addition, incorporating this Mocopi sensor system with a software application like the Blender application can aid in processing sensor data objectively.

Thus, this study explored the Mocopi sensor system integrated with the gold standard Multidirectional Reach Test (MDRT) in detecting postural reactions among healthy younger adults by analyzing the measurement accuracy of the sensor system in capturing and quantifying real-time postural changes; evaluating the intra-session reliability of the sensors to detect postural changes within repeated trials; and determining the concurrent validity of the sensor system against the gold standard MDRT.

1.3 Problem Statement

The problems addressed in this study are that many therapists rely on standardized and validated traditional clinical scales with ordinal scores to evaluate balance performance, as reported by Marchesi et al. (2021). However, these scales often lack sensitivity and are subjective, making them less effective in detecting minor changes in postural control. This subjectivity arises from the reliance on self-observation and the examiner's interpretation, which can introduce bias and lead to inconsistent outcomes (Mancini & Horak, 2010; Chen & Smith, 2019). Consequently, there is a pressing need for more sensitive, quantitative and objective methods to assess postural changes.

Recent advancements in sensor-based assessments such as force plates and IMU-based systems, have improved the objectivity of postural control evaluations. However, force plates are often impractical in community clinical settings due to their high cost, large space requirements, and lack of portability (Mancini et al., 2012; Chen et al., 2021).

Similarly, while the Vicon motion capture system combined with accelerometers can monitor postural control effectively, it is impractical for transport, requires complex setup and involves cumbersome external markers (Kelly et al., 2021). Although the HTC Vive motion-tracking system is a more affordable and user-friendly alternative, it suffers from lower accuracy and higher latency (Van der Veen et al., 2021) and requires further investigation regarding its feasibility across different populations. Thus, there is a need for a convenient and cost-effective novel sensor system capable of measuring the postural changes that traditional clinical tests may overlook.

Moreover, the literature reviews indicate inconsistencies in the placement and quantity of wearable sensors used for balance assessment (Vahid Abdollah et al., 2024). Most studies have focused on single-sensor systems to identify postural change but it may have missing data from another body part. A multisensor approach is necessary to enhance accuracy and capture information from various body regions during assessments (Tang et al., 2020). However, using multiple sensors can introduce challenges related to the complexity and obtrusiveness of the testing apparatus (Vahid Abdollah et al., 2024). Thus, fewer sensors are preferable for usability while still providing effective measurement (Pannurat et al., 2017).

Hence, it is necessary to address the problem by exploring a novel sensor system that is simple, convenient, portable, provides objective data and utilizes an optimal number of sensors attached to the body for usability in evaluating balance.

1.4 Research Questions

1. How accurately does the sensor system capture and quantify real-time postural changes among healthy younger adults?
2. How reliable are sensors to detect postural changes over repeated trials within the same session among healthy younger adults?
3. Does the sensor system demonstrate concurrent validity in detecting postural when compared to the Multidirectional Reach Test among healthy younger adults?

1.5 Aim & Objectives of Study

Aims of Study

To explore the novel sensor system for detecting postural reactions among healthy younger adults.

Objectives of Study

1. To analyze the measurement accuracy of the sensor system in capturing and quantifying real-time postural changes among healthy younger adults.
2. To evaluate the intra-session reliability of the sensors in detecting postural changes over repeated trials among healthy younger adults.
3. To determine the concurrent validity of the sensor system for detecting postural changes against the gold standard Multidirectional Reach Test among healthy younger adults.

1.6 Hypothesis of Study

Null Hypothesis (H_0)

1. The sensor system does not accurately capture and quantify real-time postural changes among healthy younger adults.
2. There is no significant intra-session reliability of the sensors in detecting postural changes over repeated trials among healthy younger adults.
3. There is no significant correlation between the postural change measurements obtained from the sensor system and the MDRT among healthy younger adults, indicating that the sensor system lacks concurrent validity.

Alternate Hypothesis (H_A)

1. The sensor system accurately captures and quantifies real-time postural changes among healthy younger adults.
2. There is a significant intra-session reliability of the sensors in detecting postural changes over repeated trials among healthy younger adults.
3. There is a significant correlation between the postural change measurements obtained from the sensor system and the MDRT among healthy younger adults, indicating that the sensor system demonstrates concurrent validity.

1.7 Operational Definition

1.7.1 Postural Reaction

A measurable and observable body response that maintains stability and balance in various situations is governed by a complex system that includes the central nervous system, as well as the sensory and motor systems (Carini, 2017).

1.7.2 Sensor System

A device that assesses and measures balance through the use of sensors. These sensors can be placed at various locations on the body to track different characteristics, such as postural sway and deviations (Kelly et al., 2021).

1.7.3 Pilot Study

A preliminary, small-scale study intended to assess the logistics and feasibility of conducting a larger study in the future. Its goal is to evaluate measurement instruments for use in the upcoming main study (In J., 2017).

1.8 Rationale of Study

Effective assessment of postural control is essential for understanding balance and preventing falls, particularly among elderly and neurological impairment populations. Traditional methods of assessing postural control often rely on subjective clinical scales, which can lead to reduced accuracy outcomes (Marchesi et al., 2021). These assessments are typically based on self-observation and subjective interpretation, making them prone to examiner bias and lacking sensitivity in detecting minor balance changes (Mancini & Horak, 2010; Chen & Smith, 2019). This limitation underscores the need for more objective and reliable assessment tools.

Recent technological advancements have introduced tools such as force plates, which provide reliable evaluations of postural sway. However, these devices are often expensive, require substantial space and lack portability, making them impractical for widespread clinical use (Mancini et al., 2012; Chen et al., 2021). Similarly, while the Vicon motion capture system offers high accuracy in evaluating balance, its complex setup involving multiple external markers and cameras can be inconvenient, particularly for individuals with mobility challenges or those who struggle to get transportation to access research facilities and assessments (Kelly et al., 2021).

To address these limitations, there is a pressing need for a novel sensor system that is convenient, lightweight, portable and capable of providing objective data for assessing postural control. This new system is believed to streamline the assessment process by reducing manpower requirements during evaluations since the data can be collected automatically, allowing assessors to focus more on monitoring the subject’s safety.

Moreover, while a multisensor approach is important for increasing measurement accuracy, it often introduces complexity and obtrusiveness into testing (Vahid Abdollah et al., 2024), such as the Vicon motion capture system. Thus, the novel sensor system consists of only six lightweight sensors strategically placed on key body structures to ensure subjects' convenience while maintaining effective measurement capabilities.

Before clinical implementation, preliminary testing of this novel sensor system must be conducted on a selected group of healthy younger adults. This study aims to explore the novel sensor system in detecting postural reactions by determining the measurement accuracy of the sensor system in capturing and quantifying real-time postural changes, the intra-session reliability of the sensors in detecting postural changes over repeated trials and the concurrent validity of the sensor system for detecting postural changes against the gold standard MDRT.

If proven effective in identifying and analyzing postural deviation, this sensor system could have significant practical applications in both assessment and rehabilitation settings. By enhancing the ability to evaluate postural control objectively, this research may contribute to improved outcomes in balance assessment protocols and fall prevention strategies.

1.9 Scope of Study

This study is a preliminary investigation aimed at exploring the novel sensor system designed to capture postural reactions among healthy younger adults. This study will focus on determining three key aspects: (1) the measurement accuracy of the sensor system in capturing and quantifying real-time postural changes; (2) the intra-session reliability of the sensors in detecting postural changes over repeated trials; and (3) the concurrent validity of the sensor system for detecting postural changes against the gold standard MDRT.

The research will specifically involve healthy undergraduate students aged 18 to 35 from Universiti Tunku Abdul Rahman, with a sample size of 58 participants to ensure statistical significance. Quantitative assessment will be conducted using six lightweight sensors strategically placed on key anatomical locations to capture real-time postural changes.

By addressing these objectives, this study aims to explore the potential applications of the novel sensor system in future assessment and rehabilitation settings. If proven effective in identifying and analyzing postural deviations, this system could facilitate more sensitive, objective and convenient evaluations of postural control impairments, ultimately aiding in the planning of appropriate interventions for targeted patient populations.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Overview

This chapter will discuss various topics by reviewing previous articles and literature. Hence, this review will provide a comprehensive overview of the current research and identify gaps that warrant further investigation. This literature review will explore existing research on postural control systems, traditional assessments of postural control, current sensor-based assessments of postural control and the sensor placement guidelines.

2.2 Postural Control System

2.2.1 Mechanisms of Postural Control

Postural control, commonly referred to as balance, is a complex skill that involves the interaction of sensory and motor systems. It plays a crucial role in independently maintaining activities of daily living. Recent studies have highlighted the understanding of the mechanism of postural control. One study by Suellen et al. (2024) described the postural control that aids in controlling body positioning in space through a dual-function system: stability and orientation. Postural stability refers to the ability to control the centre of mass (COM) in relation to the base of support while counteracting gravity. In contrast, postural orientation is the capacity to maintain alignment among the body's segments and between the body and its environment for effective perception and action.

To better understand the mechanisms of the postural control system, a study by Nashner and McCollum (1985) laid the foundation for understanding how the postural control system involved the central nervous system (CNS) and different sensory inputs that worked together to maintain postural stability and orientation in space. The study also highlighted how the vestibular, visual, and proprioceptive systems, along with specific movement strategies achieved effective postural adjustments in response to various perturbations.

The two primary movement strategies were used to maintain balance which are ankle and hip strategies. According to Blenkinsop et al. (2017), ankle strategy is typically employed during small and slow perturbations. This strategy was crucial in preserving postural equilibrium by moving the body to shift the COM forward and backward and aligning it about the ankle joint. In contrast, the hip strategy was activated during larger and faster perturbations. This strategy involved coordinated movements at the hip joint when the support surface is narrower or less stable (Blenkinsop et al., 2017). Ogaya et al. (2016) reported that healthy individuals use the ankle strategy for small perturbations but transition to the hip strategy during more challenging situations. This adaptability was crucial for maintaining balance and preventing falls, especially in varying environments. However, postural control mechanisms will change with age, leading to problems in balance and stability (Ogaya et al., 2016).

2.2.2 Age-Related Variations in Postural Control

Research indicates that postural control mechanisms significantly change affecting balance and stability as individuals age. For instance, studies have shown that optimal postural stability occurs in adults aged 34 to 44 (Patti et al., 2023). In contrast, older adults might exhibit reduced balance capabilities due to age-related factors (Patti et al., 2023). A study by Patti et al. (2023) reported that older adults often experienced a decline in sensory function such as reduced proprioception and visual acuity, which might affect sensory information integration, leading to increased postural sway and instability.

Similarly, another study by Appeadu & Bordoni (2023) supported reduced balance with age, as older adults might rely more heavily on the hip strategy due to the decreased effectiveness of the ankle strategy when facing challenges in maintaining balance. Thus, falls represent a significant health concern, especially for individuals over 60 years old or those with neurological impairment, possibly due to compromised movement strategy, leading to increased postural sway and fall risk (Appeadu & Bordoni, 2023). Hence, understanding postural control is crucial for clinical practice, particularly in assessments and rehabilitation settings.

2.2.3 Clinical Implications of Postural Control Assessment

Degani et al. (2017) conducted a comprehensive study on postural control focusing on postural sway and the limits of stability (LOS) as critical indicators for assessing balance and fall risk in an individual. Postural sway refers to the displacement of the COM while standing (Shumway-Cook & Woolacott, 2017). Degani et al. (2017) found that increased postural sway can indicate instability and a higher risk of falls, particularly in older adults or those with balance issues. LOS represents the maximum distance an individual can lean in any direction without losing balance (Shumway-Cook et al., 2023). Degani et al. (2017) emphasized that analyzing LOS is important for understanding how individuals respond to perturbations and maintain equilibrium. This study clearly clarified there was a relationship between postural sway, COM stability limits and fall risk, which had significant implications for rehabilitation strategies.

Hence, a study by Paillard and Noé (2015) discussed the importance of evaluating postural control for fall prevention and tailoring interventions based on individual assessments to enhance rehabilitation strategies and outcomes. The study emphasized various techniques available for assessing postural function or balance including clinical tests for static and dynamic balance, functional scales and quantitative measurements. However, it is still crucial to understand the underlying mechanisms of postural control and the need for valid and reliable assessment tools for rehabilitation and intervention purposes (Paillard & Noé, 2015).

2.3 Traditional Clinical Assessments of Postural Control

2.3.1 Strengths and Limitations in Berg Balance Scale (BBS)

Postural control is typically assessed through two primary conditions which are static and dynamic balance. The Berg Balance Scale (BBS) is a well-known traditional clinical assessment designed to evaluate balance and predict fall risk across various populations. It consists of 14 test items that assess both static and dynamic balance. However, one of the most significant limitations of the BBS is the ceiling effect, which can occur when the test items are not sufficiently challenging for higher-functioning individuals, leading to scores that are at or near the maximum. These effects can mask true variations in balance ability among individuals, making it difficult to detect improvements over time (Chen & Smith, 2019). This limitation highlights the necessity for more sensitive and objective tools, such as the sensor system being explored in this study to provide a more objective evaluation of postural reactions.

2.3.2 Strengths and Limitations in Functional Reach Test (FRT)

Due to its simplicity and quick administration time, the Functional Reach Test (FRT) is a widely used clinical measure (Juras et al., 2018). The FRT primarily evaluates dynamic postural control by measuring the distance between an individual's arm length and the furthest point they can reach forward while maintaining a stable base of support (Juras et al., 2018). It was developed to be more practical, efficient, and cost-effective than other testing methods. According to Smith et al. (2014), the FRT could be particularly useful in outpatient settings or for individuals with cognitive impairments who might struggle with more complex tasks in the BBS.

Several systematic reviews of the evaluation of the effectiveness and usefulness of FRT were conducted. Rosa et al. (2019) analyzed 40 studies regarding the efficacy of FRT, while Omaña et al. (2021) reviewed a total of 8 studies related to the effectiveness of FRT on fall prediction. Both reviews supported the findings that the FRT was a reliable tool for assessing balance issues across different populations, especially among older adults (Rosa et al., 2019; Omaña et al., 2021).

However, the review emphasized that FRT should not replace comprehensive fall risk assessments, suggesting a need for improved methodologies in fall risk evaluation (Omaña et al., 2021). Furthermore, studies reported that the FRT did not effectively evaluate dynamic capabilities (Rosa et al., 2019). Thus, future research should focus on more standardized protocols to enhance the reliability of the tests (Rosa et al., 2019). The limitation of the FRT in assessing dynamic capabilities further underscores the need for a novel sensor system that utilizes six sensors to capture a broader range of postural data.

2.3.3 Strengths and Limitations in Multidirectional Reach Test (MDRT)

The FRT was then modified into the Multidirectional Reach Test (MDRT) to address the limitations of the FRT, which only assesses forward reach (Juras et al., 2018). The MDRT was designed to evaluate dynamic balance by measuring the LOS of an individual in four primary directions which are forward, backward, leftward and rightward, as falls can occur in multiple directions (Juras et al., 2018). In an investigation into the correlation validity of the MDRT, significant correlations were found between the MDRT scores and those from the Berg Balance Test (BBT) and the Timed Up and Go Test (TUG) (Newton, 2001). In addition, the MDRT has been shown to possess excellent reliability with an interclass correlation coefficient (ICC) greater than 0.92 for reaching measurement in four different directions (Newton, 2001). Together the findings from previous studies have reported that the MDRT was a reliable and valid measure and commonly utilized in clinical settings for evaluating balance and risk of falls, thus enabling tailoring interventions accordingly (Newton, 2001; Tantisuwat et al., 2014; Promsorn & Taweetanalarp, 2021).

Conversely, a recent study indicated that relying solely on reaching distance might not provide a complete understanding of an individual's balance capacity (Moriyama et al., 2022). As noted by Moriyama et al. (2022) the reach distances or arm displacement were significantly affected by movement strategies such as ankle and hip strategies, recommending that these movement strategies should integrated into assessments for a more accurate and comprehensive evaluation of dynamic balance. However, currently, there is no universally accepted standard method for examining the neurological and biomechanical mechanism of postural control (Low et al., 2016).

Therefore, while traditional balance tests like BBS demonstrate good reliability, their sensitivity in capturing subtle changes in balance performance is often poor. This presents challenges in monitoring the progress and improvement over time. In addition, many clinical tests rely on subjective judgment, which could introduce the examiner's bias and variability in scoring (Mancini & Horak, 2010). Thus, it is important to explore a more sensitive tool to detect minor changes and an objective tool to assess both static and dynamic postural control.

2.4 Current Sensor-Based Assessments of Postural Control

2.4.1 Advancements in Sensor-Based Technology

Recent advancements in sensor-based technology have significantly enhanced the assessment of postural control in clinical settings by providing more comprehensive and objective evaluations (Marchesi et al., 2021). The practicality of computerized systems for evaluating balance control has increased in clinical settings, allowing physiotherapists and physicians to tailor treatments based on objective data derived from assessments of postural sway during stance (Mancini & Horak, 2010). This shift is largely attributed to advancements in posturography, a method that quantitatively evaluates balance and postural control.

2.4.2 Strengths and Limitations in Force Platform Posturography

A review by Chen et al. (2021) mentioned that force platform posturography had emerged as a pivotal technique for assessing balance by quantifying parameters related to the center of pressure (COP), which represents the point of application of ground reaction force beneath an individual standing on the force plate (Chen et al., 2021). Force plates are reliable for assessing postural sway while in a static standing position, as well as assessing dynamic balance by combining with disturbance technology such as using a mobile platform. It was vital in providing reliable and objective measurements that enhanced the understanding of postural control mechanisms (Harro et al., 2018). However, the review addressed challenges regarding the clinical applicability of force plate-based systems due to constraints such as expensive, space requirements, lack of portability and the need for a proper installation which limits their use in community clinical settings (Mancini et al., 2012; Chen et al., 2021). Thus, future developments could focus on improving the portability and affordability of objective instruments to facilitate broader clinical use (Chen et al., 2021). This highlights an opportunity for exploring a portable sensor system that can deliver similar objective measurements without these constraints.

2.4.3 Strengths and Limitations in IMU-Based Posturography

A review by Noamani et al. (2023) emphasized inertial measurement units (IMUs) based posturography represented a significant advancement in posturography for balance assessment. Unlike traditional force platforms, the IMUs-based posturography utilized accelerometers and gyroscopes to capture body motion and provided a versatile and cost-effective solution for evaluating balance. The IMUs can be attached to different body parts, facilitating assessments conducted outside the traditional clinical environment (Janc et al., 2021). A systematic review by Leirós-Rodríguez et al. (2019) studied 19 articles highlighting the reliability and validity of wearable inertial sensors such as accelerometers in evaluating balance across different populations, particularly older adults.

For example, Kelly et al. (2021) reported that the accelerometer integrated with the Vicon motion capture system was regarded as the gold standard for assessing balance and motion due to its high accuracy and extensive data collection capabilities. However, similar to the force plate-based system, this setup was impractical for home-based rehabilitation. This was largely due to the inconvenience and difficulty associated with wearing 33 external reflective markers on the body. In addition, it required eight video cameras for operation, making it impractical for transport or remote use. Furthermore, operating this system necessitates specialized knowledge for setup and management. Therefore, it is essential to assess sensor-based balance assessment tools for their practicality and usability, like the novel sensor system that offers a straightforward setup and wireless operation, allowing for conducting in various places.

Alternative systems such as the HTC Vive system offer a more cost-effective and simple tool than the Vicon motion capture system for evaluating postural stability (Van der Veen et al., 2021). The HTC Vive motion-tracking system is integrated with a custom virtual Berg Balance scale (VR-BBS) platform. Two trackers monitored the pelvis and chair position, allowing for the assessment of COM displacement while the subjects carried out the tasks based on the BBS in the VR environment. Despite its advantages, the HTC Vive system was less accurate and exhibited higher latency than the Vicon motion capture system, potentially affecting real-time performance evaluations during balance tasks (Van der Veen et al., 2021). Nevertheless, integrating IMUs with traditional assessments like the HTC Vive system could enhance the understanding of postural control as suggested by a recent study (Hanim et al., 2024). This suggestion aligns with the current study by exploring a novel sensor system integrated with traditional MDRT and further validating the effectiveness.

2.5 Sensor Placement Guidelines

2.5.1 Sensor Placement Preferences Across Studies

Research indicates that the placement of sensors on specific anatomical sites is crucial for obtaining valuable data in postural assessments (Kelly et al., 2021). A study by Ghislieri et al. (2019) reviewed 47 articles and found that 80.9% reported the sensor placement on lower back, particularly at the lumbar area of the fifth lumbar vertebrae (L5) and sacral area of the second sacral vertebrae (S2); 15% indicated the placement of the sensor on lower limb including malleolus, shank and thigh; 14.9% stated to place the sensors on the sternum area; 10.6% put it on the upper back region such as thoracic area at T4; 6.4% are placed on the upper limb which is wrists; and 2.1% placed on the forehead. Table 2.1 will provide an overview of the sensor placements found in the literature and their sources (Ghislieri et al., 2019).

Ghislieri et al. (2019) stated that a single sensor was used for posturographic evaluation in clinical practice. This sensor was often positioned on the lower back, typically at the L5 since it is close to the center of mass. Besides, Vahid Abdollah et al. (2024) indicated that sensors attached to the posterior head could effectively measure postural sway and balance parameters by providing valuable data on COM. In certain studies, sensors were applied to the lower limbs to evaluate postural strategies such as ankle and hip strategies (Bonora et al., 2017). Some studies described the positioning of sensors on the upper trunk and upper limbs for trunk tilt evaluation (Ghislieri et al., 2019). A study supported that the placement of a sensor on the shoulder could detect compensatory movements such as shoulder girdle elevation and abduction during postural sway, but not many studies on it (Borges et al., 2012). The sensors were placed at the wrist region mainly to detect independent hand movement (Tang et al., 2020).

Despite these insights, variability in sensor placement could lead to inconsistencies in measurement outcomes (Kelly et al., 2021). To address these limitations, further research was essential to establish standardized protocols for sensor placement for evaluating postural control (Kelly et al., 2021). The novel sensor system proposed in this study addresses this issue by establishing consistent sensor placement in utilizing six strategically placed sensors on wrists, ankles, lower back at the L5 and the posterior head to enhance measurement reliability.

Body segment	Locations	Number of sources	Sources
Lower back	L5	22	Baracks, et al. (2018); Baston, et al. (2016); Bonora, et al. (2017); Brown, et al. (2014); Bzduskova, et al. (2018), Chen, et al. (2018); Craig, et al. (2017); Curtze, et al. (2016); De Souza Fortaleza, et al. (2017); Doherty et al. (2017); Gago, et al. (2015); Gera, et al. (2018); Guo, et al. (2017); Halickà, et al. (2014); Heebner, et al. (2015); King, et al. (2017); Mancini, et al. (2012); Mellone, et al. (2011); Palmerini, et al. (2011); Park, et al. (2016); Rouis, et al. (2014); Spain, et al. (2012)
Lower limb	Malleolus	1	Abe, et al. (2014)
	Shank	10	Baston, et al. (2016); Bonora, et al.(2017); Brown, et al. (2014); Chiu, et al. (2017); Craig, et al. (2017); Ehsani, et al. (2018); Gago, et al. (2015); Grewal. et al. (2015); Toosizadeh, et al. (2015); Zhou, et al. (2018)
	Thigh	4	Ehsani, et al. (2018); Gago, et al. (2015); Grewal, et al. (2015); Toosizadeh, et al. (2015)
Chest	Sternum	5	Brown, et al. (2014); Craig, et al. (2017); Hsieh, et al.(2019); Nguyen, et al. (2018); Park, et al. (2016)
Upper back	T4	4	Bzduskova, et al. (2018); Guo, et al. (2017); Halickà, et al. (2014); Nguyen, et al. (2018)
Upper limbs	Wrists	2	Brown, et al. (2014); Guo, et al. (2017)
Head	Forehead	1	Abe, et al. (2014)

Table 2.1 Overview of the sensor placements found in the literature and their sources (Ghislieri et al., 2019)

2.5.2 Preferences for Use of Single and Multiple Sensors Across Study

To investigate the appropriate quantity of sensors used, Vahid Abdollah et al. (2024) mentioned that the quantity of sensors used in balance assessments remains inconsistent across studies. Most studies still preferred to utilize a single sensor system for balance assessment. While single sensors may simplify the assessment process, Tang et al. (2020) noted that such systems could reduce accuracy by omitting critical information from other body areas necessary for identifying postural change.

Conversely, Pannurat et al. (2017) advocated for multiple sensors to improve detection accuracy. However, it would introduce challenges such as increased complexity and obtrusiveness of the testing apparatus (Vahid Abdollah et al., 2024). For instance, using systems like the Vicon motion capture system requires donning or doffing numerous markers. Considering their usability, fewer sensors are preferable to place on the body landmarks (Vahid Abdollah et al., 2024). Therefore, the novel sensor system introduced in this study utilizes the optimal number of sensors while addressing usability challenges associated with complex setups.

2.6 Summary of The Literature Review

To summarize the literature review, currently, postural control involves balancing stability and body alignment, integrating sensory inputs like proprioception, vision, and the vestibular system. In addition, movement strategies like the ankle and hip strategies are key to maintaining stability during perturbations. With aging, balance declines due to reduced sensory inputs and more reliance on the hip strategy, causing increased fall risk in older adults. Thus, balance assessments in evaluating postural sway and limits of stability (LOS), help identify fall risks and guide rehabilitation. Therefore, understanding the postural control mechanism and the need for valid and reliable assessment tools is important for developing rehabilitation protocols in balance assessment and providing insight into preventing fall risks.

Traditional methods to evaluate postural control, such as BBS, FRT and MDRT remain widely used but are limited by ceiling effects, examiner bias and inadequate evaluation of dynamic capabilities. Consequently, more sensitive and objective tools such as the novel sensor system are needed to comprehensively evaluate both static and dynamic postural control.

Recent advancements in sensor-based assessments such as force plates and IMU-based systems have improved the objectivity of postural control assessment. However, force plates face challenges in clinical applicability due to cost and space requirements. Otherwise, the Vicon motion capture system is complex and inconvenient for clinical use. Although the HTC Vive motion-tracking system is simple and cost-friendly, it lacks accuracy compared to the Vicon motion capture system. Thus, exploring a sensor system that is portable, cost-effective, convenient and sensitive to detect those imperceptible by standard clinical tests is significant.

In review, sensor placement on the lower back (L5) and other body parts is crucial for accurate balance assessments. While single sensors are common, using the multisensor system is suggested to collect more information from other body parts, such as postural strategies, compensatory movement and trunk tilt evaluation. However, there is a lack of consistent sensor numbers and sensor placement positions for the sensor system in assessing postural control among the studies. Considering usability, fewer and optimal sensors are preferable and placed on the anatomical body position for evaluations. Thus, the novel sensor system introduced in this study addresses this challenge by establishing consistent sensor placement and strategically positioning sensors to specific anatomical parts.

CHAPTER 3

METHOD AND METHODOLOGY

3.1 Study Design

The research design for this study is a pilot study involving data collection from healthy younger adults in UTAR Sungai Long Campus. This pilot study is a small-scale preliminary study to evaluate potential problem areas of the novel sensor system for detecting postural changes before conducting a main study among larger populations (In J., 2017).

In this study, the dependent variables include the measurement accuracy of the sensor system, intra-session reliability of the sensors and concurrent validity of the sensor system against MDRT. The independent variables include the participant's characteristics.

3.2 Study Setting

Physiotherapy Center at Universiti Tunku Abdul Rahman (UTAR), Sungai Long Campus.

3.3 Study Population

Students from all the faculties enrolled at UTAR Sungai Long Campus.

3.4 Sample Size

58 healthy younger adult subjects.

The sample size calculation was done using the formula provided by Viechtbauer et al. (2015). According to Viechtbauer et al. (2015), this calculation offers a robust framework for planning pilot studies effectively, ensuring the study fulfills the intended purpose of identifying potential issues before large-scale trials are conducted.

The formula is designed to estimate the sample size required to detect problems in a pilot study with a 95% (0.95) confidence level and a 5% (0.05) probability of problem occurrence. The formula is:

$$n = \frac{In(1-\gamma)}{In(1-\pi)}$$

$$= \frac{In(1-0.95)}{In(1-0.05)}$$

$$\approx 58.40$$

$$= 58$$

n = required sample size

π = probability of the problem occurring in a participant

γ = confidence level

Thus, the sample size needed approximately 58 participants to achieve a high confidence level with a probability of 5% chance of problem occurrence.

3.5 Sampling Method

A convenient sampling method was used for this study. This method is considered costless, easy to conduct and a faster way to recruit participants (Elfil & Negida, 2017). In this research, undergraduate students from UTAR Sungai Long Campus were recruited using this method because it is the most effective method for the time-limited study.

3.6 Inclusion Criteria

Participants will be included if they meet the following criteria:

1. Undergraduate students enrolled in UTAR, Sungai Long Campus
2. Age of 18 to 35 years old
3. Both of the genders

3.7 Exclusion Criteria

Participants will be excluded if they have the following conditions:

1. Unwilling to participate
2. Musculoskeletal deformities
3. Neurological problems (Surgent et al., 2019)
4. Presenting acute trunk, upper and lower limb pain (Mazaheri et al., 2013)

Undergraduate students in UTAR, Sungai Long Campus with musculoskeletal deformities including diagnosed scoliosis (Dufvenberg et al., 2018), thoracic hyperkyphosis (Niibo et al., 2022), limb length discrepancy (Eliks et al., 2017) and flat foot (Takata et al., 2013) were excluded from this study. This is because these musculoskeletal conditions might lead to compensatory changes in posture and balance which may affect the accuracy of the results.

In addition, subjects with neurological problems and presenting acute trunk, upper and lower limb pain were excluded from this study because these conditions also might alter movement patterns and strategies that affect postural stability. Hence, this study focuses on a healthy population to ensure valid results by minimizing confounding factors related to pre-existing conditions and achieving a homogeneous sample that accurately reflects the population under the study.

3.8 Instruments

3.8.1 Multidirectional Reach Test (MDRT)

The MDRT acts as a gold standard tool for comparing with the novel sensor system for the validity study. It is also used to determine the limits of stability in the following four directions: forward, backward, leftward, and rightward (Tantisuwat et al., 2014).

According to Tantisuwat et al. (2014), the subject has to stand shoulder-width apart and lift the arm in front of him to the shoulder level parallel to the floor. The subjects will be instructed to extend their elbow without losing their balance and keep their heels on the ground while reaching as far forward as possible. The distance achieved is recorded in cm from the starting points determined by the third metacarpophalangeal joints lined up on the yardstick. The procedures of MDRT will be performed in forward, backward, left, and right reach directions.

3.8.2 Measuring tape

A wall-mounted instrument will be positioned at the participants' level of the acromion process during the MDRT. The measuring tape will be adjusted for every participant based on their level of acromion process.

3.8.3 Mocopi Sensor System

A novel full-body motion capture system which is developed by Sony Electronics (Sony Corporation - Mocopi | about Mocopi, www.sony.net). This system is initially designed to track human movement using lightweight sensors and a companion application, the Mocopi Application. The system comprises six small wearable sensors with inertial measurement units (IMU), each sensor measures approximately 1.26 inches in diameter and weighs only 8 grams. These sensors are fixed to attach to six specific body parts: the posterior head, lower back, bilateral ankles and dorsal wrists using Velco brands and clips. In addition, the sensors operate wirelessly with built-in rechargeable batteries, allowing for mobility during use and can be conducted in diverse environments, including indoor and outdoor settings (Kadner, 2023).

This sensor system was integrated with MDRT to detect postural changes in this research study. The six sensors were placed on the six specific sites on the participant's body while performing MDRT. These six sensors can communicate wirelessly with the iPad-installed Mocopi application via Bluetooth. In addition, the Mocopi app was used to connect sensors, calibrate settings and manage subject motion recordings. All the motion data captured from the sensor system were collected and recorded in BVH files via the Mocopi app on the iPad. The BVH files recorded in the Mocopi application were then transformed into the Blender software to process the sensor data and recorded in centimeters.

3.8.4 Plumb line instrument

Tools for assessing postural alignment, including hyperkyphosis. This method involves a vertical line, also known as a plumb line to determine the alignment of body segments. Before the experimental measurement, the plumb line assessment in lateral view was used to evaluate hyperkyphosis among UTAR Sungai Long Campus undergraduate students. The participants should be barefoot and stand in a relaxed, neutral posture with feet shoulder-width apart. The therapist will observe the alignment between the external auditory canal, acromion process, the midpoint of the iliac crest, greater trochanter, lateral condyle of the femur, posterior to knee and anterior to the lateral malleolus relative to the plumb line. In hyperkyphosis, the thoracic spine may appear excessively curved forward, causing rounded shoulders (Fabio Zaina et al., 2012). Hence, the screening was done to exclude the subjects with hyperkyphosis.

3.8.5 Navicular drop test

A test to measure the height difference of the navicular bone when transitioning from a non-wight-bearing to a weight-bearing position for assessing flat feet among UTAR Sungai Long Campus undergraduate students. Before experimental measurement, the subject was barefoot and instructed to sit on a chair with the feet on the ground. The distance from the floor to the navicular tuberosity is measured and marked on paper. The steps are repeated when the subject is in a standing position. The difference between the non-weight-bearing measurement and the weight-bearing measurement is the navicular drop value. According to Roth et al. (2013), a drop greater than 10mm is typically considered indicative of excessive foot pronation and may suggest flatfoot. Hence, the screening was done to exclude the subjects with flat feet.

3.8.6 iPad and laptop

Devices that will receive the data from the sensor system via Bluetooth connection. In addition, the devices will be installed with Blender software to abstract and record the sensor data in the units of centimeters (cm). They are also used to analyze all the MDRT and sensor data collected.

3.9 Procedures

3.9.1 Recruitment of Participants

This pilot study requires 58 undergraduate students aged between 18 and 35 in UTAR Sungai Long Campus and were recruited face-to-face or through social media such as WhatsApp and Instagram. A Google form consisted of the consent form of the participants and a personal data protection notice was given to the participants once they were interested in joining. The Google form was also included explaining the research study's aim, objectives and inclusion and exclusion criteria. The demographic data including their contact number, gender, age, height and body weight were obtained from the Google form once they agreed to join the research study. In addition, this form also required the participants to answer some questions mainly in screening the participants who fulfilled all the inclusion criteria.

3.9.2 Preparation Before the Experimental Measurement

Data collection was conducted at KA345, UTAR Sungai Long Campus Physiotherapy Center. Participants who provided their demographic data and relevant information and fulfilled all the inclusion criteria were included in the study. A screening session was performed for all participants before the data collection, including the plumb line assessment and navicular drop test. Participants who showed flat foot or thoracic hyperkyphosis for the screening tests were excluded from the study.

Then, the participants got a briefing on explaining the study's methods including the sensor system, sensor placement and MDRT methods. Several safety precautions for the study had been informed to the participants such as performing the test barefoot and on a flat surface. Besides, the participant also was instructed to remove all the gadgets from the body including the smartphone and smartwatch to minimize the possible interference that may affect the sensor’s performance and the accuracy of the results.

3.9.3 Progression of the Validity Measurement

Familiarization with the MDRT was conducted three to four times among the participants to ensure they understood the MDRT procedures. Before starting the experimental measurement, the participants were given 30 seconds of rest.

After rest, six sensors were attached at both sides of the ankles, hip (over L5), both sides of the wrists and posterior head. Before data collection, participants were calibrated by performing specific poses and inputting the height. Then, the participants were asked to perform MDRT simultaneously they were assessed using the sensor system that detects the postural changes. The measurement was done for three trials.

3.9.4 Progression of Reliability Measurement

No familiarization with the MDRT was conducted before the experimental measurements. Participants were instructed to perform MDRT in four directions simultaneously assessed by the sensor system. Due to time constraints, three trials for each reaching direction were completed within a single session on the same day for intra-session reliability measurement (Héctor Pereiro-Buceta et al., 2021). 30 seconds of rest was given between the trials.

3.9.5 Data Processing for MDRT

The starting and ending reach distances for MDRT in four directions were recorded. The distance difference between the starting and ending positions of the four reach categories was calculated in centimeters (cm). The average of each reach category among the three trials was taken. All the data from MDRT was recorded on the laptop in Excel.

3.9.6 Data Processing for Sensor System

The motion recording from the Mocopi sensor system was recorded on the iPad in a BVH file. The BVH file was then transformed into the Blender application to abstract the sensor data in units of centimeters. The distance difference between the starting and ending positions of the four reach categories was abstracted based on the Y-axis using the Blender application. The average of four reach categories among three trials was calculated. All the data from the sensor system was recorded on the laptop in Excel.

3.10 Statistical Analysis

The data collected will be analyzed using the IBM Statistical Package for the Social Science (SPSS) software version 30.0 and Microsoft Excel to produce study outcomes.

Demographic data including age, height, body weight and body mass index (BMI) are analyzed by descriptive statistics and reported in means (M) and standard deviations (SD).

The measurement accuracy of the sensor system is also analyzed by descriptive statistics and reported the sensor and MDRT readings as the mean (M), standard deviation (SD) and mean difference for all four reach categories. This will help to understand how close the sensor measurements are to the mean and standard deviation scores of MDRT.

The inta-session reliability of the sensor system is evaluated by the Intraclass Correlation Coefficient (ICC) and Conbach’s alpha to assess the consistency of measurements from the sensors over repeated three trials within the same session. This statistical method quantifies how reliably the sensors detect postural changes between three trials of measurements.

The concurrent validity of the novel sensor system for detecting postural changes against the gold standard MDRT is determined by the correlation analysis by calculating the Spearman correlation coefficient and its significance level when the dataset is not normally distributed.

3.11 Ethical Approval

This study will be subjected to ethical approval by the Scientific and Ethical Review Committee (SERC) of Universiti Tunku Abdul Rahman (UTAR). Informed consent will be obtained from all eligible participants in this study. They signed the form indicating they agreed to be involved in the research. Participants have the right to withdraw from the study at any time. Potential risks, benefits, and data confidentiality will be sternly and thoroughly addressed to the participants upon receiving the informed consent form.

CHAPTER 4

RESULTS

4.1 Chapter Overview

This chapter will present the findings and statistical analysis after the data collection. It begins with the descriptive analysis to overview demographic data. Followed by the descriptive analysis of the sensor system measurement accuracy. Normality Tests on average distance obtained from MDRT and sensor system were presented. Then, the inferential analysis was used to test the study objectives and hypotheses including intra-session reliability and concurrent validity of the sensor system. All the results were displayed in an organized manner, including a comprehensive table and relevant graphs with explanations below each table or graph to enhance the understanding of the results.

4.2 Demographic Data of Participants

Demographic Data	M ± SD
Age	22.10 ± 0.89
Height, cm	164.36 ± 7.55
Body Weight, kg	58.59 ± 12.91
BMI, kg/m^2	21.62 ± 4.04

Table 4.1 Demographic Data of Participants (N=58)

Table 4.1 shows a snapshot of the participant demographics. It shows the means (M) and standard deviations (SD) of the age, height, weight, and Body Mass Index (BMI) of 58 participants.

Initially, a total of 60 subjects from UTAR undergraduate students aged 18 to 35 volunteered to participate in the study. 58 of the 60 participants who met the inclusion criteria were recruited to the study. Two out of the 60 participants were excluded from the research due to the presence of flat feet after the screening test.

The participants have an average age of 22.10 years old, with an SD of 0.89, indicating that most participants are close in age. The average height of the participants was 164.36 cm, with an SD of 7.55 cm, showing moderate variability in height among the participants. Besides, the mean body weight is 58.59 kg, with an SD of 12.91 kg, suggesting a broader range of body weights within the group. Moreover, the average BMI is 21.62 kg/m^2, with an SD of 4.04 kg/m^2, indicating the participants are generally within the normal BMI category.

4.3 Analysis of the Measurement Accuracy of Sensor System

This subsection provides an overview of the descriptive analysis of the first study's objective regarding analyzing the sensor system measurement accuracy. The analysis will compare the mean (M) and standard deviation (SD) values of the average distances achieved by the sensor system and MDRT across four reach categories: forward reach (FR), backward reach (BR), leftward reach (LR) and rightward reach (RR). Additionally, mean differences between the scores or average distances achieved on the sensor system and MDRT were highlighted to address the objective and hypothesis. All the data analyses were performed using IBM SPSS Software Statistics version 30.

Sensor System	M ± SD
FR (cm)	10.05 ± 9.35
BR (cm)	3.64 ± 4.95
LR (cm)	5.56 ± 3.96
RR (cm)	7.02 ± 4.72

Table 4.2 Scores on the Sensor System of Participants

MDRT	M ± SD
FR (cm)	28.80 ± 6.14
BR (cm)	19.22 ± 6.10
LR (cm)	18.12 ± 4.49
RR (cm)	17.12 ± 4.40

Table 4.3 Scores on MDRT of Participants

Sensor System and MDRT	Mean Difference
FR (cm)	18.75
BR (cm)	15.58
LR (cm)	12.56
RR (cm)	10.10

Table 4.4 Mean Difference Between Scores on Sensor System and MDRT

By comparing Tables 4.2 and 4.3, the mean scores on the sensor system were significantly lower than those on the MDRT across all the reach categories.

For forward reach (FF), the sensor system recorded a mean of 10.05 cm compared to the MDRT mean of 28.80 cm, resulting in a mean difference of 18.75 cm. Backward reach (BR) showed a sensor mean of 3.64 cm against an MDRT mean of 19.22 cm, with a mean difference of 15.58 cm. Leftward reach (LR) had a sensor mean of 5.56 cm compared to the MDRT mean of 18.12 cm, resulting in a mean difference of 12.56 cm. Rightward reach (RR) recorded the mean of the sensor system as 7.02 cm compared to the mean of MDRT as 17.12 cm, leading to a difference of 10.10 cm.

The standard deviations for the sensor system readings are relatively high, indicating substantial measurement variability. The SD for FR is notably high at 9.35 cm. Similarly, BR has an SD of 4.95 cm, while LR and RR have SDs of 3.96 cm and 4.72 cm respectively.

The analysis demonstrates that the sensor system shows larger measurement discrepancies compared to MDRT, as indicated by higher mean differences and SD across all reach categories of the sensor system score. Thus, suggesting that the sensor system does not accurately capture and quantify the postural changes.

4.4 Inferential Analysis Test

The subsection will outline the inferential analysis for the study. To address the second and third objectives and hypotheses of the study, an Intraclass Correlation Coefficient (ICC) will be used to test three trials of the sensor system measurement and a Spearman Correlation Coefficient will be used to test measurements on MDRT and the sensor system if the datasets are not normally distributed. According to the study by Rovetta (2020), a normality test will be performed to determine whether the sensor system and MDRT data obtained can reasonably be assumed to follow a normal distribution before proceeding with parametric analyses.

In addition, a concise explanation of the test will be provided, followed by the interpretation of the outcomes, with the results presented in tabular form. Moreover, all analyses are conducted using IBM SPSS Statistics, version 30.0.

4.4.1 Normality Test on Average Distance of MDRT

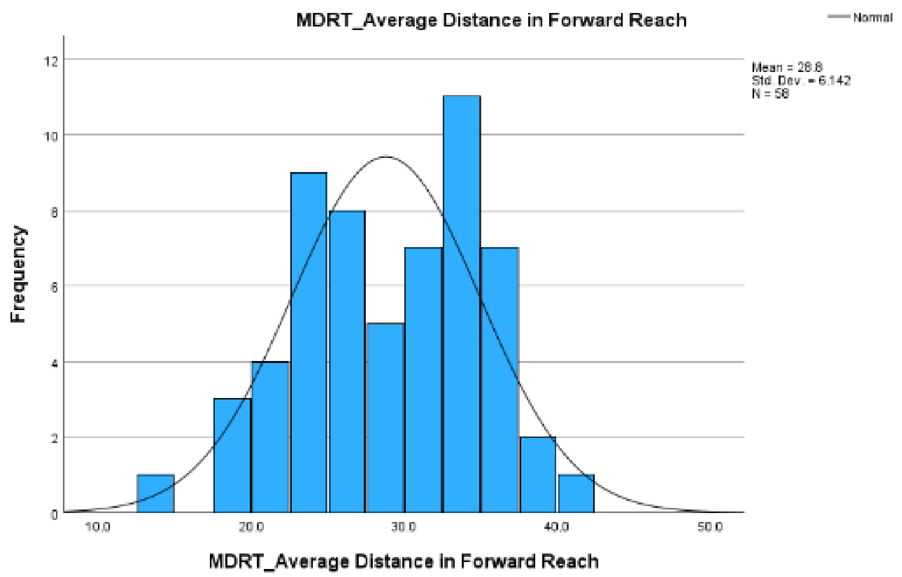

Figure 4.1 The average distance in three trials of forward reach using MDRT

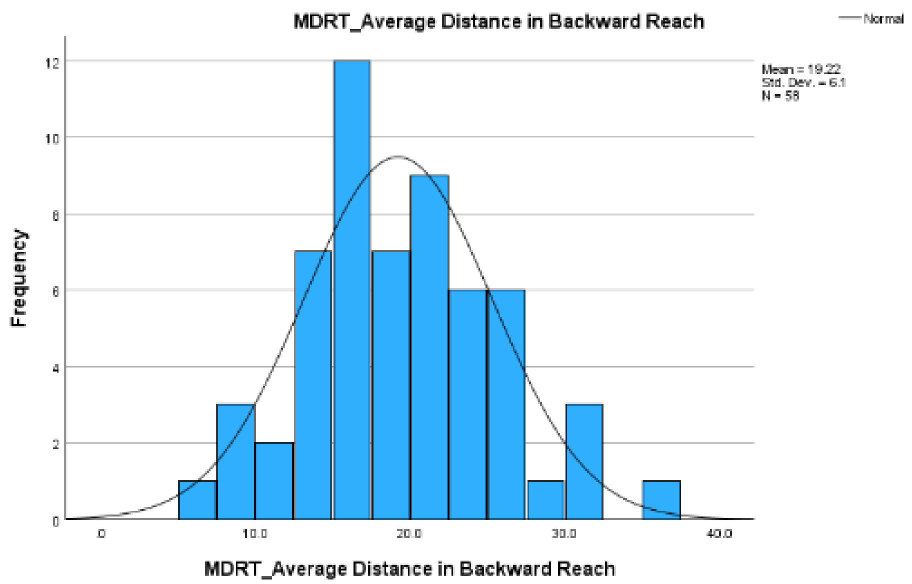

Figure 4.2 The average distance in three trials of backward reach using MDRT

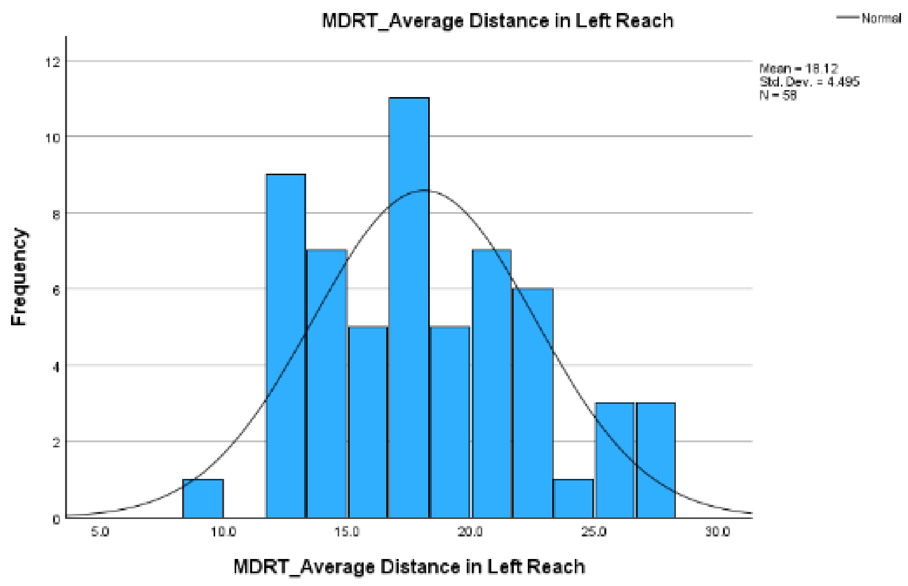

Figure 4.3 The average distance in three trials of leftward reach using MDRT

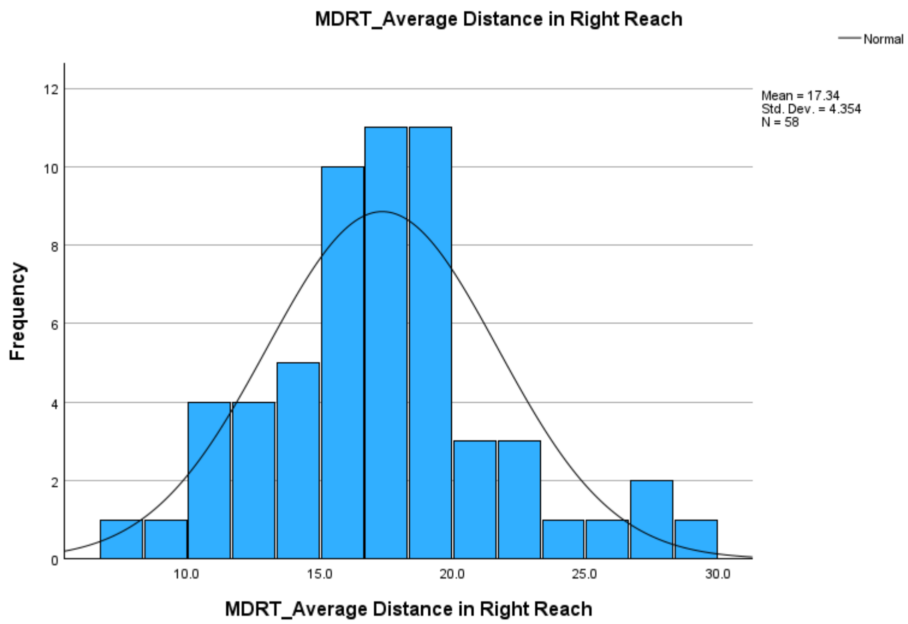

Figure 4.4 The average distance in three trials of rightward reach using MDRT

MDRT	Kolmogorov-Smirnov Sig.
FR	0.066
BR	0.200
LR	0.200
RR	0.181

P>0.05 = normal

P<0.05 = not normal

Table 4.5 Tests of normality for average scores of MDRT in four reach categories

Figures 4.6 to 4.9 show the average distance in three trials of each reaching direction using MDRT presented in histograms with a distribution curve. All four datasets from Figure 4.6, Figure 4.7, Figure 4.8 and Figure 4.9 demonstrate normal distribution, as suggested by the bell curve and symmetrical shapes of the histograms.

The Kolmogorov-Smirnov test results presented in Table 4.5 provide additional support for the findings. The p-values of FR, BR, LR and RR are 0.066, 0.200, 0.200 and 0.181 respectively. Since these p-values exceed the standard significance level of 0.05, the FR, BR, LR and RR datasets are normally distributed.

4.4.2 Normality Test on Average Distances of Sensor System

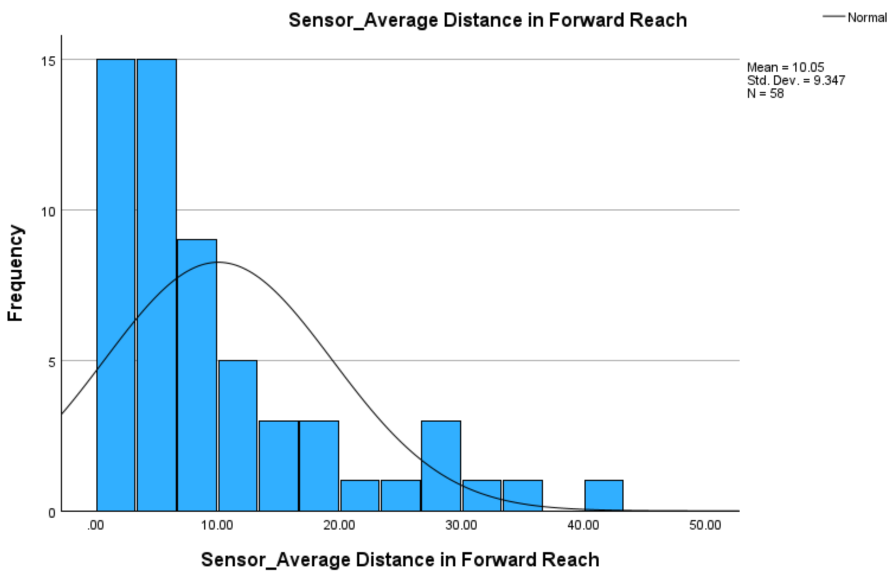

Figure 4.5 The average distance in three trials of forward reach using the sensor system

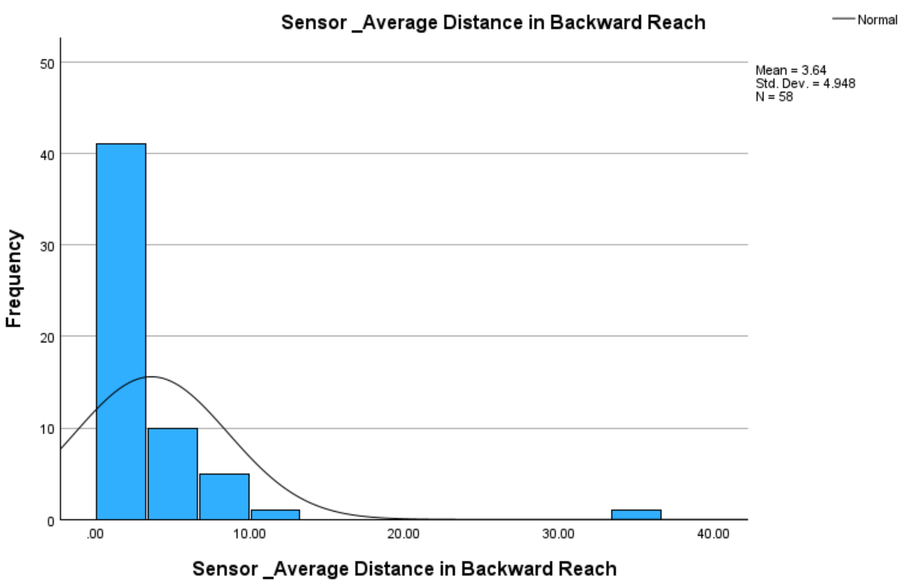

Figure 4.6 The average distance in three trials of backward reach using the sensor system

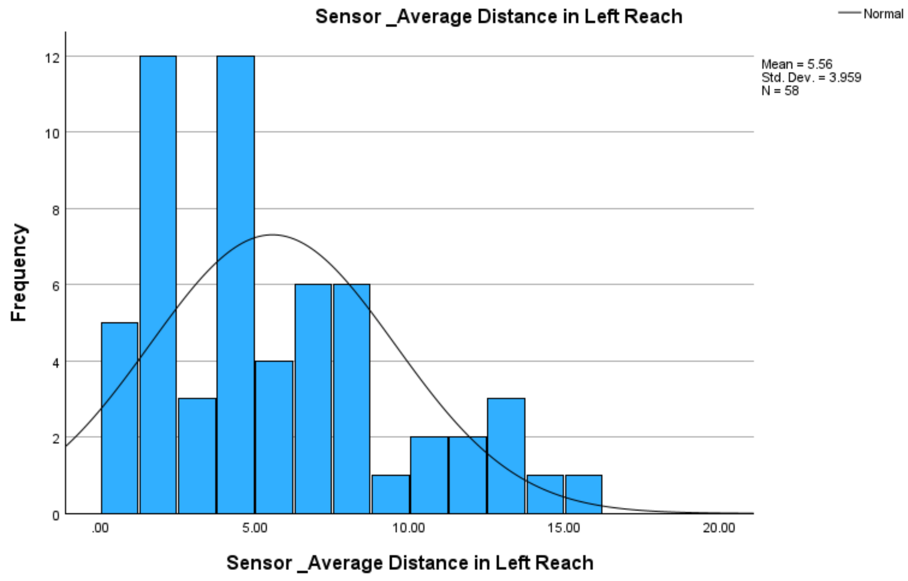

Figure 4.7 The average distance in three trials of leftward reach using the sensor system

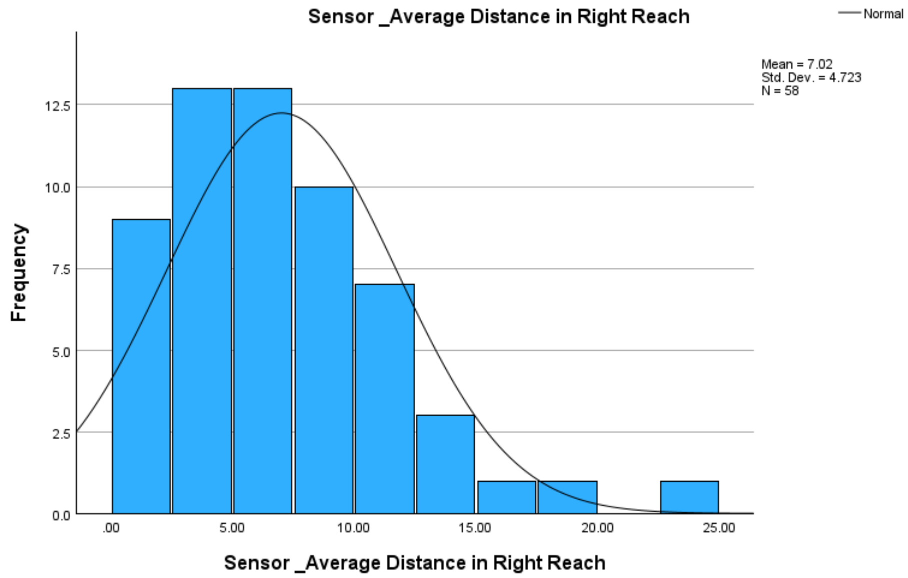

Figure 4.8 The average distance in three trials of rightward reach using the sensor system

Sensor System	Kolmogorov-Smirnov Sig.
FR	<0.001
BR	<0.001
LR	0.007
RR	0.046

P>0.05 = normal

P<0.05 = not normal

Table 4.6 Tests of normality for average scores of the sensor system in four reach categories

Figures 4.10 to 4.13 show the average distance in three trials of each reaching direction using the sensor system presented in histograms with a distribution curve. All four datasets from Figure 4.10 to 4.13 demonstrate a positively skewed curve, indicating the dataset is not normally distributed.

The Kolmogorov-Smirnov test results shown in Table 4.6 further strengthen the results. The p-values of FR and BR are less than 0.001, while the p-values of LR and RR are 0.007 and 0.046 respectively. Since these p-values are less than the standard significance level of 0.05, indicating the FR, BR, LR and RR datasets are not normally distributed.

4.4.3 Analysis of Intra-Session Reliability of the Sensor System

Sensor System	M ± SD	Cronbach's alpha	ICC	95% CI	Sig.
FR	29.73±27.80	0.821	0.604	0.465-0.725	<0.001
BR	10.74±14.85	0.907	0.765	0.665-0.844	<0.001
LR	16.69±11.89	0.837	0.631	0.496-0.746	<0.001
RR	20.82 ±14.33	0.835	0.628	0.494-0.744	<0.001

Two-way mixed effects model where people effects are random and measure effects are fixed.

Table 4.7 Intra-session reliability across 3 trials of the sensor system measurement in each reach directions

The presented data indicate the mean (M), standard deviation (SD), Cronbach's alpha, intraclass correlation coefficient (ICC), 95% confidence intervals (CI), and significant values of four reaching categories using the sensor system.

FR has a mean of 29.73 cm with a standard deviation of 27.80 cm; BR has a mean of 10.74 cm with a standard deviation of 14.85 cm; LR has a mean of 16.69 cm with a standard deviation of 11.89 cm; and RR has a mean of 20.82 cm with a standard deviation of 14.33 cm.

The ICC of BR is the highest at 0.765, indicating good reliability. FR follows with an ICC value of 0.604, LR with an ICC value of 0.631 and RR with an ICC value of 0.628, all reflecting moderate to good reliability levels. These ICC values suggest that the sensor system consistently measures postural changes within repeated trials in the same session.

The 95% confidence interval for BR ranges from 0.665 to 0.844. For FR, the CI interval ranges from 0.465 to 0.725. LR and RR have confidence intervals of 0.496 to 0.746 and 0.494 to 0.744 respectively.

To strengthen the findings, Cronbach's alpha values further support the reliability findings by measuring internal consistency across all reach categories (Ahmad et al., 2024). BR again achieves the highest score of 0.907, suggesting excellent reliability. It is followed by FR at 0.821, LR at 0.837 and RR at 0.835, indicating good internal consistency. All values exceed the cut-off values of 0.70. This strong internal consistency across trials indicates that the sensor system measurements are not only reliable but also coherent within each reach category.

All reported significance values are less than 0.01, confirming that the observed reliability coefficients are statistically significant. This statistical significance strengthens the argument that the sensor system can reliably detect postural changes over repeated trials.

Overall, the analysis demonstrates that the sensor system exhibits significantly good intra-session reliability across three trials in each reach category.

4.4.4 Spearman Correlation Coefficient result between MDRT and sensor system

Sensor System	MDRT Measurement	Correlation coefficient (r_s)	Sig. (2-tailed)
Sensor system FR	MDRT FR	-0.307	0.020
Sensor system BR	MDRT BR	-0.145	0.281
Sensor system LR	MDRT LR	-0.285	0.031
Sensor system RR	MDRT RR	-0.052	0.702

Correlation is significant at the 0.05 level (2-tailed).

Table 4.8 Spearman correlation coefficient results between the sensor systems and the MDRT measurements

Based on Table 4.6, the Spearman correlation coefficient for the sensor system and MDRT measurements in FR is -0.307, with a significance level (p-value) of 0.020. This shows a significant poor negative correlation between the sensor systems and the MDRT measurements in FR.

In contrast, the correlation between the sensor system and MDRT measurements in BR has a correlation coefficient of -0.145 with a p-value of 0.281. This indicates no significant correlation between the sensor systems and the MDRT measurements in BR.

Moreover, the correlation coefficient for the sensor system and MDRT measurements in LR is -0.285, with a p-value of 0.70. This shows a significant poor negative correlation between the sensor systems and the MDRT measurements in LR.

Lastly, the correlation between the sensor system and MDRT measurements in RR has a correlation coefficient of -0.052, with a p-value of 0.702. This indicates no significant correlation between the sensor systems and the MDRT measurements in RR.

Overall, the results highlight that only the sensor system measurements in FR and LR have significantly poor negative correlations with MDRT measurements. Additionally, the sensor system measurements in BR and RR show no significant correlation with MDRT measurements. The overall relationship is not strong enough to support the alternate hypothesis. Thus, there is no significant correlation between the measurements from the sensor system and the gold-standard MDRT.

CHAPTER 5

DISCUSSION

5.1 Chapter Overview

This chapter will outline the discussion of the findings presented in the results section and relate them to the research objectives. It will then address the theoretical implications, practical implications, the study's limitations, recommendations for future research, and conclude the research project.

5.2 Discussion

The study explored the novel sensor system for detecting postural deviation among healthy younger adults aged from 18 to 35 years old. This is to test the hypotheses regarding (1) the measurement accuracy of the sensor system in capturing and quantifying real-time postural changes, (2) the intra-session reliability of the sensors in detecting postural changes over repeated trials, and (3) the concurrent validity of the sensor system for detecting postural changes against the gold standard MDRT.

The key findings of the study were: (1) the sensor system does not accurately capture and quantify real-time postural changes (2) there is a significant intra-session reliability of the sensors in detecting postural changes over repeated trials, and (3) there is no significant correlation between the postural change measurements obtained from the sensor system and the MDRT, indicating that the sensor system lacks concurrent validity.

5.2.1 Poor Measurement Accuracy of the Sensor System

The results of this study revealed larger measurement discrepancies of the sensor system with the MDRT data, as evidenced by higher mean differences and standard deviations across all reach categories. These findings indicate that the sensor system lacks the necessary precision in its readings to assess postural changes. Hence, it can be concluded that the sensor system did not accurately capture and quantify real-time postural changes.

This preliminary test utilized the Mocopi sensor system to detect postural changes. Notably, there have been no prior studies directly investigating this application for assessing balance or postural control. The most recent research by Shin et al. (2024) examined the use of Mocopi sensor devices for tracking movements in real-time for virtual reality applications. However, the results of the current pilot study contrast with the earlier study that suggested Mocopi sensor devices could accurately track movements in real-time (Shin et al., 2024). In this study, the sensor system did not achieve similar levels of accuracy in capturing and quantifying real-time postural changes.

When comparing these findings with previous research that utilized a multiple-sensor approach involving placements on the wrists, ankles and lower back for detecting postural changes, which is similar to the sensor placements in the current pilot study. However, those previous studies achieved higher accuracy in balance assessments, which is opposite to the current findings (Marjan Nassajpour et al., 2024; Kelly et al., 2021).

The unexpected results observed in the pilot study can be attributed to several factors that may have influenced sensor measurement accuracy. One possible reason for the poor measurement accuracy could be sensor connectivity issues, as highlighted by Sieberts et al. (2024). Such problems may arise from environmental factors such as electromagnetic interference, which can disrupt communication between the sensors and receiving devices. These connectivity problems can lead to data loss and incomplete measurements (Sieberts et al. (2024).

Besides, the lack of sensitivity of the Mocopi sensor system might limit its ability to detect small changes in reaching distance that are critical for accurately assessing postural deviations. Spooner et al. (2024) noted that if sensors lack sufficient sensitivity to detect minor postural shifts, they may overlook essential data points necessary for accurate assessments. This issue could explain why the current study found larger discrepancies between sensor readings and MDRT readings, ultimately leading to an overall failure to capture real-time postural changes effectively.

Thus, this pilot study addresses a critical gap by highlighting the challenges encountered while implementing this novel sensor system in real-world settings for evaluating postural deviations. It raises awareness about potential limitations in the novel sensor system, such as poor connectivity and lack of sensitivity to detect minor reaching distance changes.

5.2.2 Good Intra-session Reliability of the Sensor System

The study demonstrates that the sensor system exhibits good internal consistency and intra-session reliability across three trials in four reach categories. This finding indicates that the sensors used in the study are both consistent and reliable for measuring postural changes within a single session, thereby supporting the hypothesis that there is significant intra-session reliability of the sensors in detecting postural changes over repeated trials.

This result aligns with the previous systematic review focused on wearable inertial sensor systems, which highlighted their intra-session reliability in measuring postural control performance. Out of 47 studies evaluated, eight studies specifically investigated the intra-session reliability of sensor measurements, reporting values ranging from good to excellent (ICC=0.03 to 0.97) (Baker et al., 2021; Johnston et al., 2019).

When comparing these findings with prior research, the differences arise in terms of population focus. This pilot study investigates healthy younger adults, a demographic that typically exhibits better balance and postural control compared to previous studies that focused on older adults or those with specific health conditions (Baker et al., 2021; Johnston et al., 2019). This difference in population can significantly affect the generalizability of the findings because younger healthy individuals may not exhibit the same variability in postural reactions as older adults or those with health issues, potentially leading to different reliability outcomes (Chow et al., 2019).

Moreover, the difference also arises in terms of the accuracy of measurements. Many previous studies have demonstrated both high intra-session reliability and accuracy in their findings (Johnston et al., 2019). In contrast, although the sensor system in the current study was reliable, it failed to provide accurate readings. A study by Arash Atrsaei et al. (2020) supported the findings by reporting that while the consistency across trials reflects good reliability, the individual measurements may exhibit inaccuracies. This suggests that participants can maintain their relative performance levels despite potential absolute measurement errors during the investigation.

The primary reason for the good intra-session reliability of the sensor system in detecting postural changes, but inaccurate readings, may be due to the sensors, especially those based on inertial measurement units (IMUs) being inaccurately calibrated before testing. Such systematic error can result in consistent but inaccurate data across trials, yielding high reliability but without accurate absolute values (Sigcha et al., 2023).

The current pilot study addresses a critical gap in understanding how inaccurate sensor calibration impacts both reliability and accuracy in postural change assessments. It also underscores the need for future research aimed at improving sensor accuracy and bridging the gap between reliability and accuracy to enhance the utility of the sensor system in clinical and research settings. In addition, it provides insight into the reliability of the novel sensor system specifically designed to detect postural changes in younger healthy adults, an area that has been less explored, compared to older populations and disease populations.

5.2.3 Lacks Concurrent Validity of the Sensor System Against the MDRT

The results of this study indicated that the sensor system measurements for FR and LR demonstrated significantly poor negative correlations with the measurements from the MDRT. In contrast, the sensor system measurements for BR and RR showed no significant correlation with MDRT measurements. These findings suggest that there is some level of correlation between the sensor system and the MDRT measurements, particularly for forward and leftward reaching directions. However, the overall relationship is not strong enough to support the hypothesis that the sensor system provides valid measures of postural changes comparable to those obtained from the MDRT. Consequently, there is no significant correlation between the postural change measurements obtained from the sensor system and the gold standard MDRT, indicating that the sensor system lacks concurrent validity.

The MDRT itself has been validated as a reliable tool for measuring postural deviations, with studies showing high interclass correlation coefficient (ICC) and significant correlations with other validated balance tests (Newton, 2001). The weak correlations observed in this study indicate that although the sensor system can capture some aspects of postural changes in certain reaching directions, it may not be sensitive enough to reliably reflect true reaching capabilities as assessed by the gold standard MDRT. This lack of correlation suggests limitations in the sensor system's ability to provide a comprehensive balance assessment.

These findings contrast with previous studies that reported excellent validity and reliability for wearable inertial sensors in the parameterization of the Functional Reach Test (FRT) by providing specificity as well as reliable and valid kinematic measures in assessments (Pires et al., 2020; Merchán-Baeza et al., 2014). Furthermore, when considering balance assessment besides the MDRT or FRT, these results also contrast with previous studies that utilized the IMU sensor-based systems which can effectively enhance other clinical balance tests, such as the Timed Up and Go (TUG) test, Berg Balance Scale (BBS) and Mini-BESTest, through automated sensor data collection (Li et al., 2023; Sample et al., 2017; Shahzad et al., 2017).

However, some studies encountered similar issues to those observed in the current study. These studies revealed that their explored sensor system did not provide sufficiently valid measures due to inconsistent correlations with traditional assessments, suggesting that their findings may not yet support clinical use (Johnston et al., 2019; Miller et al., 2020).

In addition, recent studies have increasingly focused on evaluating various sensor systems for balance assessment by validating them against the Vicon motion capture system, which is recognized as the gold standard in motion analysis. These previous studies contrast with current findings, as they demonstrated promising validity and highlighted the potential of their study's new sensor technologies to enhance balance assessment methodologies, showing a strong correlation with the established Vicon motion capture system (Merriaux et al., 2017; van der Veen & Thomas, 2021; Kelly et al., 2021).

One potential reason for the lack of concurrent validity of the Mocopi sensor system compared to the MDRT could be the differing operational principles of the sensor system and MDRT. The MDRT is a functional assessment that directly measures how far a subject can reach through physical movement. In contrast, the sensor system may rely on indirect metrics such as angular displacement (Pires et al., 2020), which may not align well with the physical reach distances measured by the MDRT. This discrepancy in operational principles could lead to differences in measurement outcomes, resulting in a poor correlation with MDRT results. Therefore, utilizing the Vicon motion capture system as a benchmark may provide a more effective and accurate investigation into the concurrent validity of the novel sensor technologies, as these systems may operate under similar principles compared to traditional assessments like the MDRT (Merriaux et al., 2017; van der Veen & Thomas, 2021; Kelly et al., 2021).

Additionally, another critical reason for these unexpected results could be the sensor system's inability to accurately and sensitively detect postural changes (Francisco et al., 2024). This limitation may be due to inadequate sensor scoring software and a lack of sophisticated algorithms for processing sensor data. In this study, the Blender App was used to analyze sensor data but primarily focused on measuring reach distances along the Y-axis without adequately considering distances along the X and Z axes. This oversight may lead to an incomplete and inaccurate representation of an individual’s postural deviations during reaching. As Tsai et al. (2023) noted, postural adjustment involved vertical, lateral and rotational movements. Such oversight of these issues may result in a lack of correlation between measurements from the sensor system and those from the MDRT.

Lastly, this study highlighted potential limitations in existing methodologies, such as sensor data scoring methods. Recently, there has been no native application that accurately and efficiently processes Mocopi sensor data. Consequently, the third-party application, Blender Application was used. However, the study indicated that Blender may not effectively match in processing the Mocopi sensor data, leading to invalid and inaccurate results compared to MDRT results. This underscores the need for additional studies to explore alternative software solutions that could enhance measurement accuracy and encourage ongoing research to improve Mocopi sensor technology. Furthermore, it also emphasizes the necessity of enhancing the accuracy, reliability and validity of this novel sensor system before its clinical application.

5.3 Theoretical Implications

This research study advances existing theories on sensor technology by providing insights that contribute to established theoretical frameworks. Although the study's findings indicate limitations in measurement accuracy and concurrent validity, they still offer valuable perspectives for further theoretical exploration.

This study employed a portable, cost-friendly, convenient and simple setup novel sensor system, specifically designed to detect postural changes. This study highlights the importance of affordability and accessibility in technological innovations for rehabilitation purposes. By emphasizing how emerging technologies can be integrated into assessments without imposing significant financial barriers or requiring cumbersome setups, this research contributes to the broader discourse on making such sensor technology accessible to individuals with mobility problems.

Besides, this study strengthens the theoretical foundations of technology acceptance models, especially for older adults, by exploring the impact of this novel sensor system on performance in monitoring their postural deviations. It highlights how convenience sensor designs can enhance adoption rates among individuals who may be hesitant to engage with complex technologies. The positive findings regarding intra-session reliability may suggest that users can trust the sensor system to provide consistent measurements, which is crucial for fostering acceptance.

In addition, the lack of significant correlation between the sensor system measurements and the MDRT raises important questions regarding the validity of new measurement tools in clinical settings. The novel sensor system may offer convenience, but it must also demonstrate robust accuracy to be considered a reliable alternative to assess postural changes before clinical use. This situation underscores the critical need for future studies to investigate both technological novelty and empirical validation. By addressing these aspects, researchers can better understand the effectiveness of emerging sensor technologies and their potential integration into clinical practice.

5.4 Practical Implications

This study presents several practical implications that could significantly impact various fields. Although the study's findings indicated limitations in measurement accuracy and concurrent validity, the insight gained can still inform real-world applications.

From a policy perspective, the study underscores the need to implement wearable sensor technologies in community healthcare settings rather than solely relying on traditional assessment methods. Policymakers should advocate for further research aimed at enhancing the accuracy and validity of the novel sensor system before its widespread adoption in clinical practice. Moreover, by recognizing the potential benefits of low-cost and convenience sensor systems for monitoring postural reactions, healthcare policies could support initiatives that integrate these technologies into the community, particularly for populations at risk of falls or mobility impairment.

Last but not least, the findings from this pilot study contribute to ongoing discussions in the field of assessment and rehabilitation technology. By highlighting both the strengths and weaknesses of the novel sensor system, this research encourages further advancements in sensor technology to address current limitations. This study also serves as a call to action for future research aimed at refining the sensor system to improve its accuracy and validity in capturing real-time postural changes. Additionally, this work opens avenues for interdisciplinary collaborations among engineers, clinicians and researchers to develop a more comprehensive and sensitive sensor system capable of reliably assessing balance across diverse populations.

5.5 Limitations of the Study

One of the primary limitations of this study is the time constraint imposed on data collection. The study was conducted as a one-time participation event for each subject. Therefore, this study was only able to assess intra-session reliability for three trials in four reaching categories using the MDRT and sensor system within a single session. While intra-session reliability was measured, the absence of a multi-session design prevented exploration of inter-session reliability, test-retest reliability and inter-rater reliability over a 24-hour interval.

In addition, the study faced limitations in the scope of reliability testing due to the limited time. By focusing solely on intra-session reliability, the generalizability of the findings is restricted. This limitation may result in an incomplete understanding of how consistently the sensor system captures postural changes over extended periods.

Moreover, the study encountered limitations related to software capabilities for processing sensor data. Currently, there is no native application that accurately and efficiently processes Mocopi sensor data. Additionally, insufficient time was allocated to explore and implement alternative software solutions for more effective sensor data handling. As a result, only one software application, Blender Application, was utilized in this study due to its common use in data processing. However, the findings indicated that Blender software may not effectively match in processing Mocopi sensor data after collection. Thus, without adequate exploration of extra software options, the study may have missed opportunities to optimize sensor data collection and analysis. This limitation could potentially affect the overall accuracy of measurement obtained from the sensor system.

Another significant concern is measurement bias arising from calibration errors during data collection. During the phase of sensor data processing using the Blender application, it was noted that calibration was not performed correctly for some participants, causing the data to be inaccurate. If the sensors were not properly calibrated before the experimental measurement, systematic errors in data collection may occur. For instance, although the sensor system may consistently measure postural deviations within a single session, inaccuracies introduced by poor calibration could lead to incorrect assessment when compared to MDRT results. Thus, while the intra-session measurements of the sensor system were reported as reliable, they could still be misleading if calibration issues were present.

Lastly, intermittent loss of Bluetooth connectivity of sensors during data collection further exacerbates measurement bias. The sensors occasionally disconnected from the iPad, which led to gaps in data or incomplete motion recording obtained. For example, if Bluetooth connectivity was lost while performing reaching tasks in the MDRT, it would prevent the sensors from capturing significant postural deviations and reaching distances, leading to an underestimation of an individual’s reach abilities. Such interruptions not only affect overall sensor data quality but also introduce variability that could skew results.

5.6 Recommendation for Future Study

Future studies should consider incorporating a longitudinal design that allows for repeated measures across multiple days or sessions. This approach will provide a more robust evaluation of the sensor's reliability, including inter-session reliability, test-retest reliability, or inter-rater reliability. By conducting multiple trials over several sessions, researchers gain a better understanding of how the sensor system performs in terms of long-term reliability. Addressing these limitations in future research will be crucial for validating the sensor system's performance and enhancing its applicability in clinical settings.

Besides, future research should evaluate various software solutions for Mocopi sensor data abstraction and analysis beyond the Blender Application used in this study. By testing different software options, researchers can identify tools that optimize sensor data collection efficiency, accuracy and processing capabilities. This exploration may uncover software that better manages sensor data, thereby improving overall measurement outcomes.

To mitigate measurement bias due to calibration errors, future studies should establish rigorous calibration procedures before data collection. This could involve verifying that all six sensors accurately reflect the correct movements in motion capture recordings and recalibrating any sensors that show incorrect joint movements before data collection. Implementing such measures will help minimize systematic errors and enhance data accuracy.

Furthermore, to effectively address the impact of environmental factors, including electromagnetic interference on Bluetooth connectivity during data collection, future studies should focus on establishing a controlled environment. This controlled setting should be designed to minimize external influences that could skew results. For example, conducting experiments in spaces free from electronic devices such as handphones and smartwatches can help eliminate sources of electromagnetic interference. In addition, maintaining consistent distances between the sensors and the connecting devices will ensure stable connectivity. By ensuring strong connections, researchers can enhance data integrity and reduce variability caused by incomplete motion recordings from the sensors.

5.7 Conclusion

In summary, the pilot study highlights the key findings regarding the measurement accuracy, intra-session reliability and concurrent validity of the Mocopi sensor system for detecting postural reactions. The study found that while the Mocopi sensor system demonstrates strong intra-session reliability across multiple trials, it fails to accurately capture and quantify real-time postural changes. The sensor system also lacks validity, as it lacks of significant correlation between the measurements from the sensor system and the established gold standard MDRT.

This research is a preliminary test that can serve as a foundation for future studies aimed at enhancing and reevaluating the sensor systems for detecting postural reactions. Despite the limitations of the study's results, its exploration of a cost-effective, convenient, portable and user-friendly sensor system underscores the importance of making advanced technologies accessible, particularly to older adults or individuals with mobility impairment. By demonstrating that such technologies can be integrated into assessments without imposing significant financial burdens and accessibility challenges.

Moreover, the study's results address a notable gap in research concerning the application of novel sensor technologies for postural control assessment. Specifically, this study emphasizes the importance of refining sensor connectivity issues through a controlled experimental setting and enhancing sensor sensitivity to detect minor postural deviations. The findings also highlight the necessity for improved calibration procedures and explore alternative software solutions to mitigate measurement bias and enhance overall sensor data accuracy.

Furthermore, there is a clear need for a longitudinal study focused on older adults and disease-specific populations to achieve a more robust evaluation of the sensor's reliability. Such research will provide a better understanding of how the sensor system performs in terms of long-term reliability across diverse populations. Overall, this study paves the way for future investigations that can lead to more effective and objective balance assessment tools in clinical practice.

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APPENDIX A – ETHICAL APPROVAL FORM

UNIVERSITI TUNKU ABDUL RAHMAN
Wholly Owned by UTAR Education Foundation (Company No. 578227-M)

Re: U/SERC/78-363/2024

23 September 2024

Mr Muhammad Noh Zulfikri bin Mohd Jamali
Head, Department of Physiotherapy
M. Kandiah Faculty of Medicine and Health Sciences
Universiti Tunku Abdul Rahman
Jalan Sungai Long
Bandar Sungai Long
43000 Kajang, Selangor

Dear Mr Muhammad Noh,

Ethical Approval For Research Project/Protocol

We refer to your application for ethical approval for your students' research project from Bachelor of Physiotherapy (Honours) programme enrolled in course UMFD3026. We are pleased to inform you that the application has been approved under Expedited Review.

The details of the research projects are as follows:

No	Research Title	Student's Name	Supervisor's Name	Approval Validity
1.	The Effect of Diaphragm Muscle Exercise on Dynamic Balance among Post-COVID-19 Older Adults in Klang Valley, Malaysi	Goh Le Yi	Ms Premala a/p Krishnan	23 September 2024 – 22 September 2025
2.	Relationship Between Cognitive Domains, Dynamic Postural Stability and Fall Risk in Elderly Individuals with Mild Cognitive Impairment: A Pilot Study	Chaw Jade Wern		
3.	Smartphone Addiction and Its Relationship with Forward Head Posture and Grip Strength Among University Students in Klang Valley	Chuar Yu Cheng	Mr Chew Wai Hoong	
4.	Dynamic Balance and Life-Space Mobility Among Community Dwelling Older Adults: A Correlation Study	Grace Wong Mui Kar		
5.	Relationship Between Neck Disability, Sleep Quality, and Perceived Stress Among University Students in Klang Valley	Low Jun Kai		
6.	Association Between Medial Longitudinal Arch and Body Mass Index Among Young Adults in Klang Valley and Selangor, Malaysia	Mahaasiri a/p Kamalavallo	Ms Ambusam a/p Subramaniam	
7.	Effectiveness of Mulligan's Traction Straight Leg Raise Technique on Young University Students with Symptoms of Restless Leg Syndrome	Lim Chun Qi	Mr Tarun Amalnerkar Ms Swapneela Jacob	
8.	Effect of 4-week Inspiratory Muscle Training (IMT) Program on Young Adult with Mild Obstructive Sleep Apnea (OSA)	Sia Cai Ni	Mr Tarun Amalnerkar Ms Swapneela Jacob Mr Sathish Kumar Sadagobane	

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No	Research Title	Student's Name	Supervisor's Name	Approval Validity
9.	Assessment Of Diagnostic Clinical Reasoning Skills Among Undergraduate Physiotherapy Students	Jason Ho Yi Zeng	Mr Avanianban Chakkarapani	23 September 2024 – 22 September 2025
10.	Awareness, Knowledge, Attitude and Perception of Active Isolated Stretching Among Physiotherapy Academics and Students in a Private University: A Cross Sectional Study	Law Jing Tien		
11.	Knowledge Of Quadriceps Angle (Q-Angle) Among Physiotherapy Students	Tay Yu Xin		
12.	Cortical Excitability and Body Awareness in Individuals with Adolescent Idiopathic Scoliosis: An Exploratory Study	Mark Isaac Fernandez	Dr Deepak Thazhakkattu Vasu	
13.	Exercise Interventions in Primiparous Women for the Prevention and Management of Pelvic Floor Dysfunction: A Systematic Review	Jenny Peng Mei Shi		
14.	Exploring the Novel Sensor System for Detecting Postural Reactions Among Healthy Younger Adults: A Pilot Study	Ooi Xin Rou		
15.	Prevalence of Chronic Fatigue Syndrome (CFS) and Its Association on Quality of Life and Sleep Quality Among Young Adults: A Cross-sectional Study	Delphine Yeo Sze Qi	Mr Sathish Kumar Sadagobane Co-Supervisor: Mr Tarun Amalnerkar	
16.	Association Between Level of Ergonomic Knowledge and Prevalence of Neck Pain Among Part-time Postgraduate Students in Klang Valley	Ng Jia Xuan	Mr Sathish Kumar Sadagobane Co-Supervisor: Mr Edwin Gaspar	
17.	Effectiveness of Kinesiotaping with Static Stretching and Proprioceptive Neuromuscular Facilitation Stretching for Gastrocnemius Tightness Management Among Adults	Tan Jia Yin	Ms Heaw Yu Chi	
18.	Awareness, Knowledge and Perceptions of Chronic Fatigue Syndrome/ Myalgic Encephalomyelitis Between Student and Working Physiotherapists: A Comparative Study	Tee Yee Pei		
19.	Effect of Pulmonary Rehabilitation on Dyspnea and Quality of Life Among Chronic Obstructive Pulmonary Disease Patients: A Systematic Review	Chin Jay Ven	Mr Imtiyaz Ali Mir	
20.	Efficacy of Music Therapy and Mindfulness Meditation on Blood Pressure and Mental Health Among University Students	Tan Pei Chen		
21.	Effects of Music Therapy on Haemodynamic Variables and Mental Health in Patients with Coronary Artery Disease: A Systematic Review	Foong Ei Yan		
22.	Effects of Different Phases of the Menstrual Cycle on Daytime Drowsiness and Muscular Fatigue Among Recreational Female Badminton Players	Lee Kae Shyan	Mr Muhammad Noh Zulfikri Bin Mohd Jamali Co-supervisor: Mr Tarun Amalnerkar	
23.	Association between Gastrocnemius Tightness, Hallux Valgus and Physical Activity Among University Students	Chong Yi Xian	Ms Siti Hazirah Binti Samsuri	
24.	The Prevalence of Lower Urinary Tract Symptoms (LUTS) and Its Associated Risk Factors Among Male University Students	Gan Xinyi		
25.	Examining Doms Reduction in Recreational Versus Competitive Athletic Populations	Jona Kong Zong Na	Ms Kamala a/p Krishnan	
26.	Effectiveness of Virtual Reality Games on Hand Movement and Strength rehabilitation in Stroke Patients: A Systematic Review	Rachel Hew Zi Qi		

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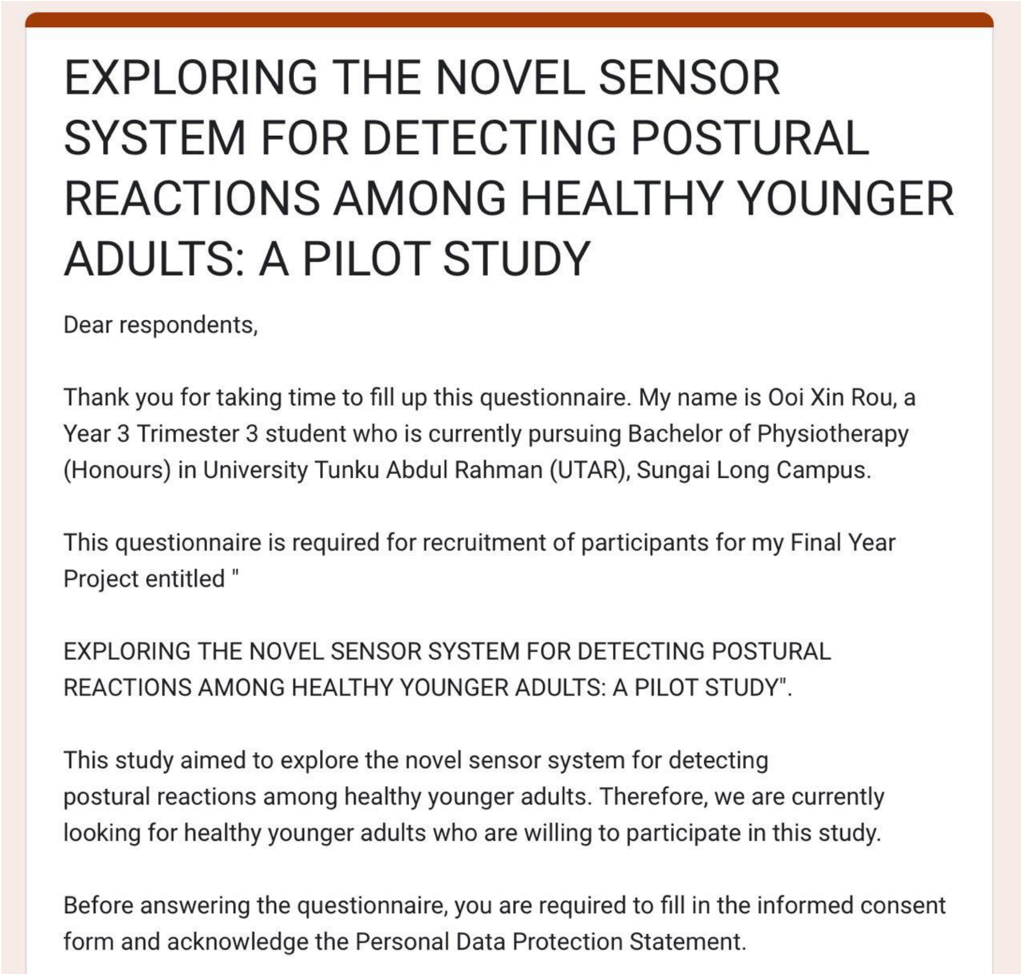
Tel: (603) 9086 0288 **Fax**: (603) 9019 8868
Website: www.utar.edu.my

APPENDIX B – INFORMED CONSENT FORM



EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY

Dear respondents,

Thank you for taking time to fill up this questionnaire. My name is Ooi Xin Rou, a Year 3 Trimester 3 student who is currently pursuing Bachelor of Physiotherapy (Honours) in University Tunku Abdul Rahman (UTAR), Sungai Long Campus.

This questionnaire is required for recruitment of participants for my Final Year Project entitled "

EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY".

This study aimed to explore the novel sensor system for detecting postural reactions among healthy younger adults. Therefore, we are currently looking for healthy younger adults who are willing to participate in this study.

Before answering the questionnaire, you are required to fill in the informed consent form and acknowledge the Personal Data Protection Statement.

Informed Consent Form

Dear respondents,
You are invited to participate in a research study conducted by OOI XIN ROU, from Bachelor of Physiotherapy (HONS) in Universiti Tunku Abdul Rahman (UTAR), Sungai Long Campus.

Please read this information sheet and contact me to ask any questions that you may have before agreeing to take part in this study.
You are welcome to help to complete this study if you are **aged 18-35 years old undergraduate student in UTAR, Sungai Long Campus**.

Purpose of the Research Study
The purpose of this study is to explore the novel sensor system for detecting postural reactions among healthy younger adults by determining (1) the measurement accuracy of the sensor system in capturing and quantifying real-time postural changes, (2) the intra-session reliability of the sensors in detecting postural changes over repeated trials, and (3) the concurrent validity of the sensor system, for detecting postural changes against the gold standard Multidirectional Reach Test.

Procedures
Before you proceed to the study, you will be asked to fill up a questionnaire which will take around 5 minutes to complete. This questionnaire consists of two sections:

Section 1 – To obtain informed consent
Section 2 – To collect demographic data

If you agree to be in this study and fulfill the inclusion criteria, you will be asked to come to the physiotherapy center at KA345, UTAR Sungai Long Campus to participate in this study. Six sensors will be placed on specific body regions at the same time a balance test, a Multidirectional Reach Test, will be performed. The test will take around 20 minutes to complete. The data will then be collected and analyzed.

Length of Participation
One-time participation only.

Risks and Benefits
No risk will be involved throughout the current study.
There are no direct benefits to participating in this study, but the results of the study will help the rehabilitation understand, plan the appropriate interventions and review the effectiveness of the program with the application of the novel sensor system.

Confidentiality
No information that will make it possible to identify you will be included in any reports to the university or in any publications.
Research records will be stored securely and only approved researchers will have access to the records.

Voluntary Nature of the Study
Participation in this study is voluntary. If you withdraw or decline participation, you will not be penalized or lose benefits or services unrelated to the study. If you decide to participate, you may decline to answer any question and may choose to withdraw at any time.

Contacts and Questions
If you have any questions, clarifications, concerns, or complaints about the research, the researcher conducting this study can be contacted at 010-8485342 (Mabel), or by email to oxr720@1utar.my.

My research supervisor, Dr. Deepak Thazhakkattu Vasu can be contacted by email at deepak@utar.edu.my if there are any inquiries, concerns or complaints about the research and there is a wish to talk to someone other than individuals on the research team.

Please keep this information sheet for your records.

If you have read the above statements and agree to participate in this study, please tick the checkbox. *

- ○ I have been notified by you and that I hereby understand, consent and agreed to participate in this study
- ○ I disagree to participate in this study

APPENDIX C – PERSONAL DATA PROTECTION NOTICE

Personal Data Protection Notice

Please be informed that in accordance with Personal Data Protection Act 2010 ("PDPA") which came into force on 15 November 2013, Universiti Tunku Abdul Rahman ("UTAR") is hereby bound to make notice and require consent in relation to collection, recording, storage, usage and retention of personal information. *

1. Personal data refers to any information which may directly or indirectly identify a person which could include sensitive personal data and expression of opinion. Among others it includes:
a) Name
b) Identity card
c) Place of Birth
d) Address
e) Education History
f) Employment History
g) Medical History
h) Blood type
i) Race
j) Religion
k) Photo
l) Personal Information and Associated Research Data

2. The purposes for which your personal data may be used are inclusive but not limited to:
a) For assessment of any application to UTAR
b) For processing any benefits and services
c) For communication purposes
d) For advertorial and news
e) For general administration and record purposes
f) For enhancing the value of education
g) For educational and related purposes consequential to UTAR
h) For replying any responds to complaints and enquiries
i) For the purpose of our corporate governance
j) For the purposes of conducting research/ collaboration

3. Your personal data may be transferred and/or disclosed to third party and/or UTAR collaborative partners including but not limited to the respective and appointed outsourcing agents for purpose of fulfilling our obligations to you in respect of the purposes and all such other purposes that are related to the purposes and also in providing integrated services, maintaining and storing records. Your data may be shared when required by laws and when disclosure is necessary to comply with applicable laws.

4. Any personal information retained by UTAR shall be destroyed and/or deleted in accordance with our retention policy applicable for us in the event such information is no longer required.

5. UTAR is committed in ensuring the confidentiality, protection, security and accuracy of your personal information made available to us and it has been our ongoing strict policy to ensure that your personal information is accurate, complete, not misleading and updated. UTAR would also ensure that your personal data shall not be used for political and commercial purposes.

Consent:
6. By submitting or providing your personal data to UTAR, you had consented and agreed for your personal data to be used in accordance to the terms and conditions in the Notice and our relevant policy.

7. If you do not consent or subsequently withdraw your consent to the processing and disclosure of your personal data, UTAR will not be able to fulfill our obligations or to contact you or to assist you in respect of the purposes and/or for any other purposes related to the purpose.

8. You may access and update your personal data by writing to us at oxr720@1utar.my or 010-8485342 (Mabel).

- ○ I have been notified and that I hereby understood, consented and agreed per UTAR above notice.
- ○ I disagree, my personal data will not be processed.

APPENDIX D – QUESTIONNAIRE FORM (DEMOGRAPHICS)

Demographic Data

Contact Number *

Your answer

Age *

Your answer

Gender *

- ◯ Male
- ◯ Female

Height (cm) *

Your answer

Body Weight (kg) *

Your answer

Do you have diagnosed scoliosis? *

- ◯ Yes
- ◯ No

Do you have a difference between the legs 's length (limb length discrepancy)? *

- ◯ Yes
- ◯ No

Do you have any neurological problems? *

- ◯ Yes
- ◯ No

Have you recently experienced intense pain around your trunk or upper and lower extremities? *

- ◯ Yes
- ◯ No

Do you have flat foot? *

- ◯ Yes
- ◯ No
- ◯ Not Sure

Do you have abnormal rounding of upper back (hyperkyphosis)? *

- ◯ Yes
- ◯ No
- ◯ Not Sure

APPENDIX E – NAVICULAR DROP TEST

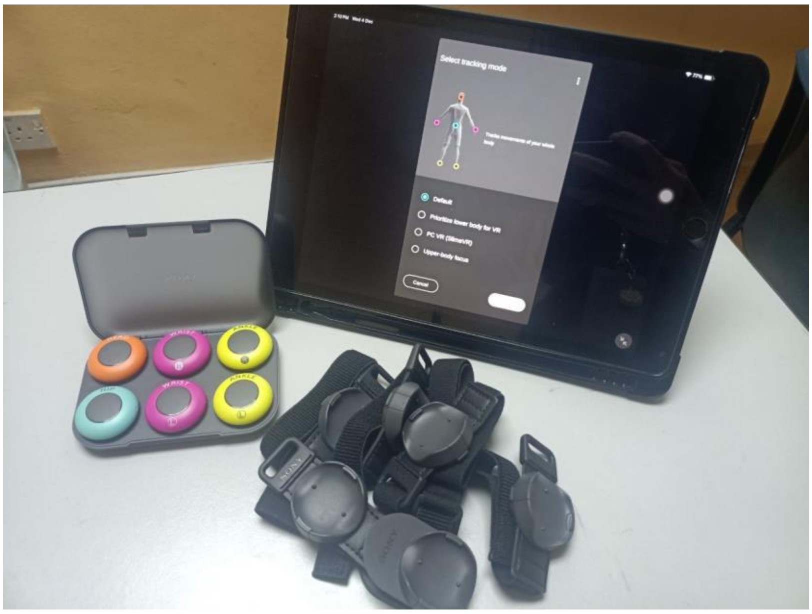
Sitting Position

Standing Position

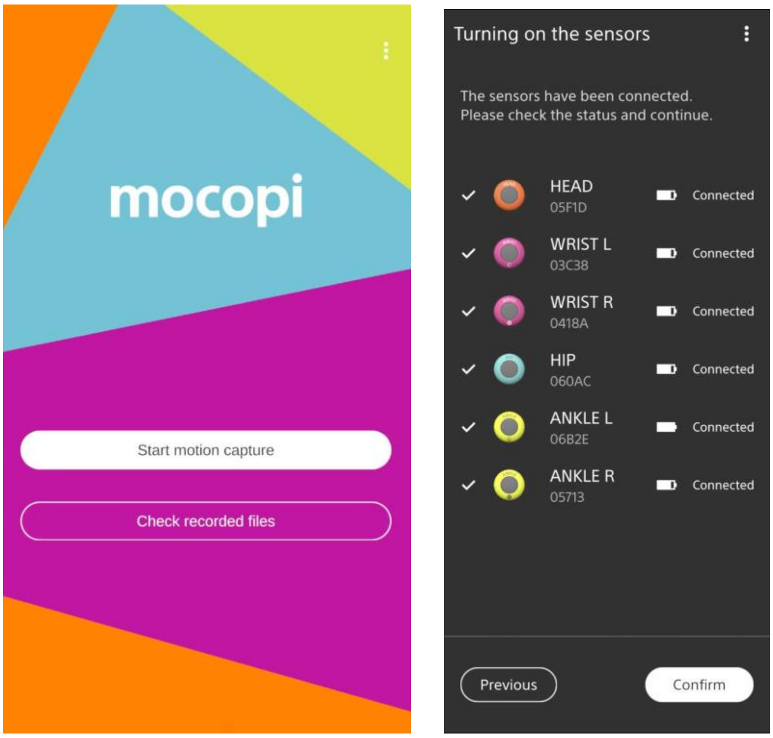
APPENDIX F – PLUMB LINE ASSESSMENT

Lateral View

APPENDIX G – SENSOR SYSTEM SETUP



iPad-installed Mocopi app and six sensors with Velco brands and clips

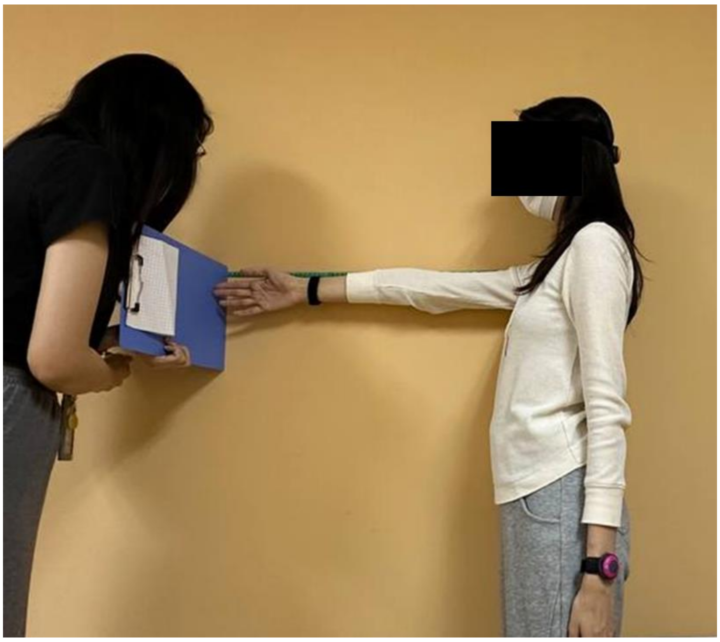


Six sensors connect wirelessly with the iPad-installed Mocopi app via Bluetooth

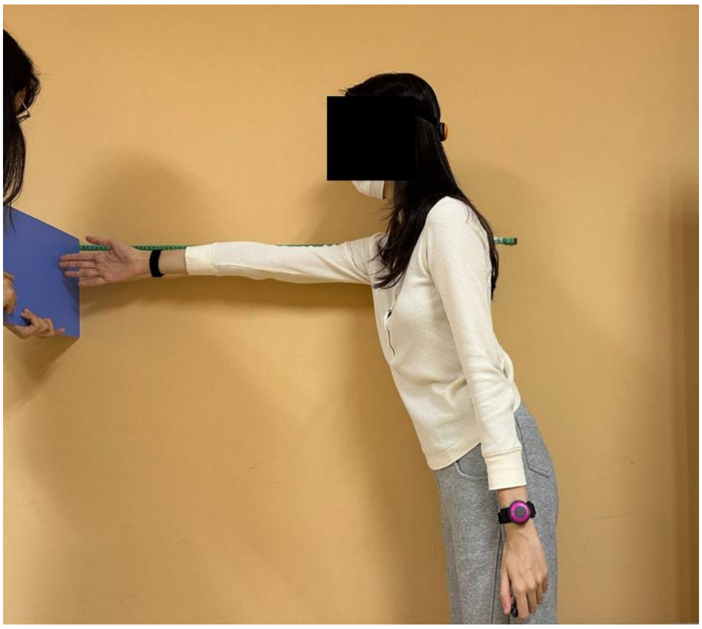
APPENDIX H – SENSOR PLACEMENT

Sensors are placed on the posterior head, lower back (L5), dorsal wrists, and ankles (above lateral malleolus)

APPENDIX I – MDRT WITH SENSOR SYSTEM MEASUREMENT

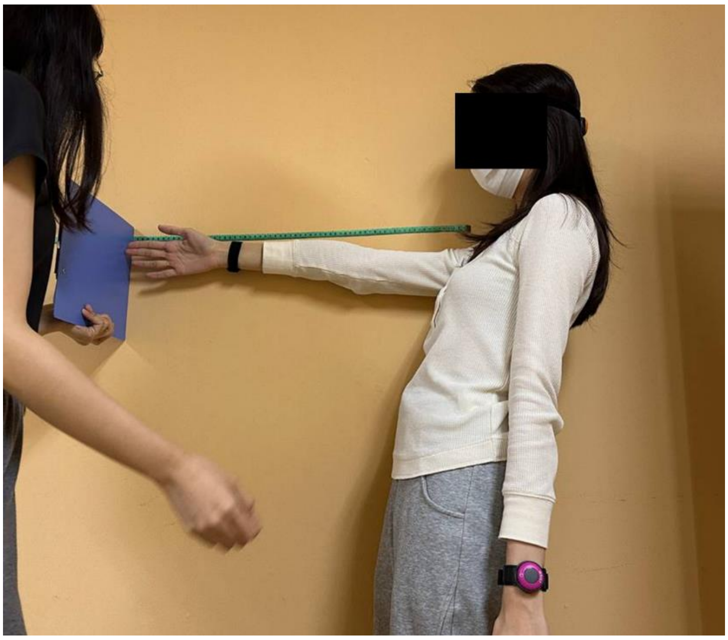


Initial Reading Taking for Forward Reach



Final Reading Taking for Forward Reach

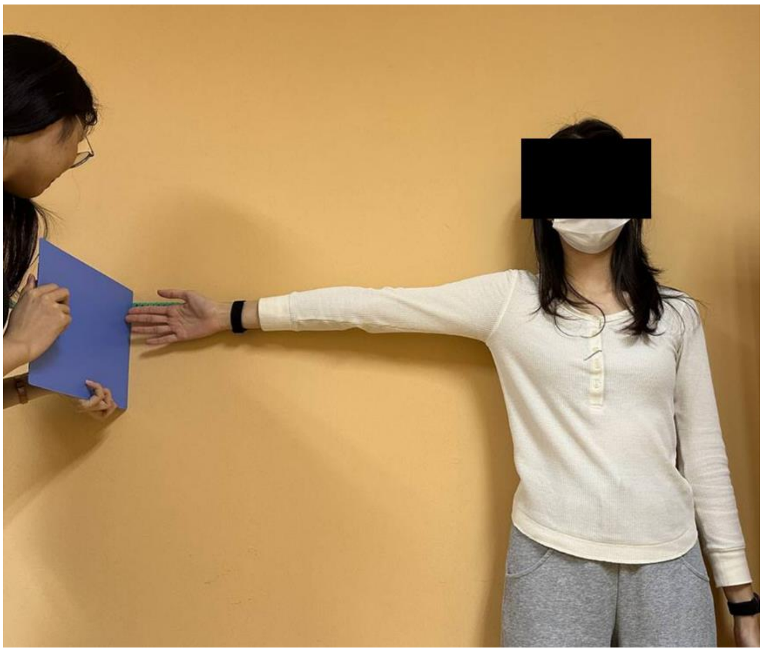
Initial Reading Taking for Backward Reach



Final Reading Taking for Backward Reach

Initial Reading Taking for Leftward Reach

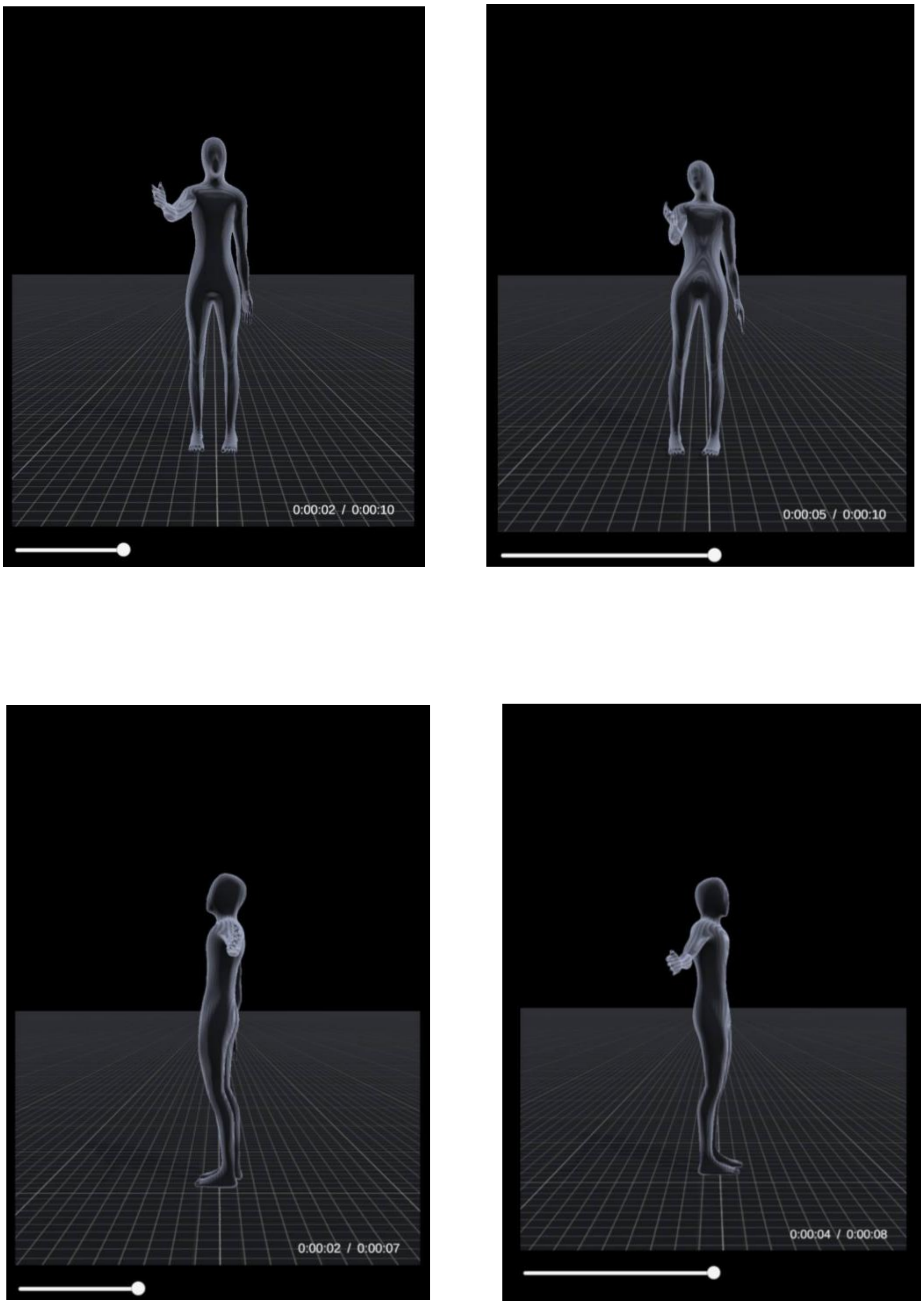
Final Reading Taking for Leftward Reach



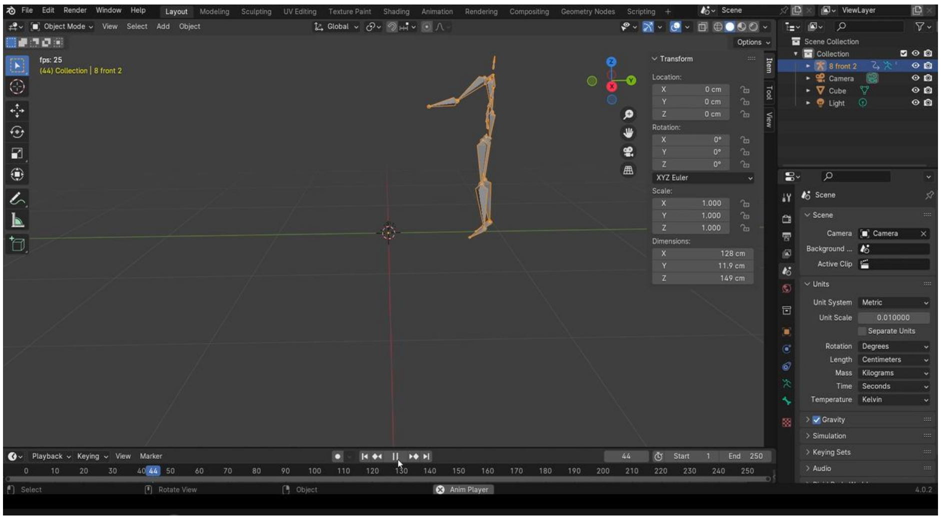
Initial Reading Taking for Rightward Reach

Final Reading Taking for Rightward Reach

APPENDIX J – SENSOR DATA ABSTRACTING



Motion recording from the sensor system automatically saved in BVH files in the Mocopi app on iPad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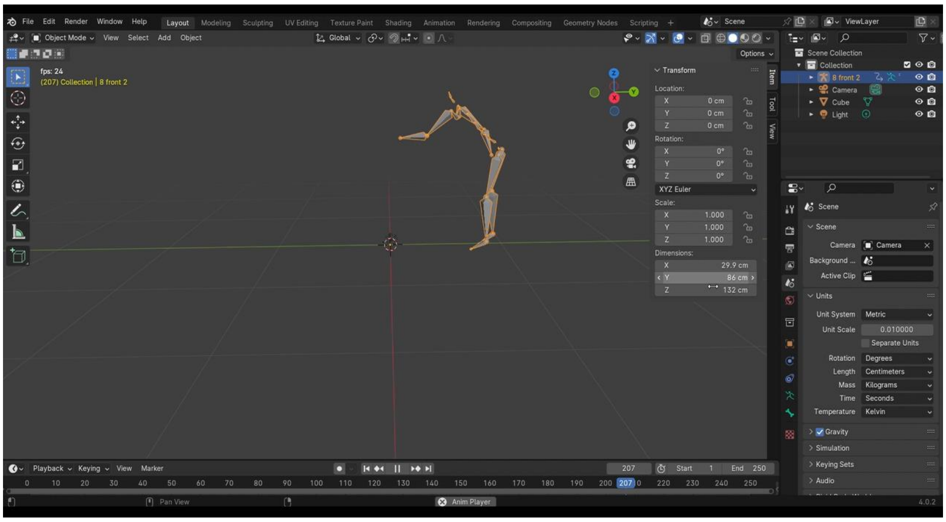
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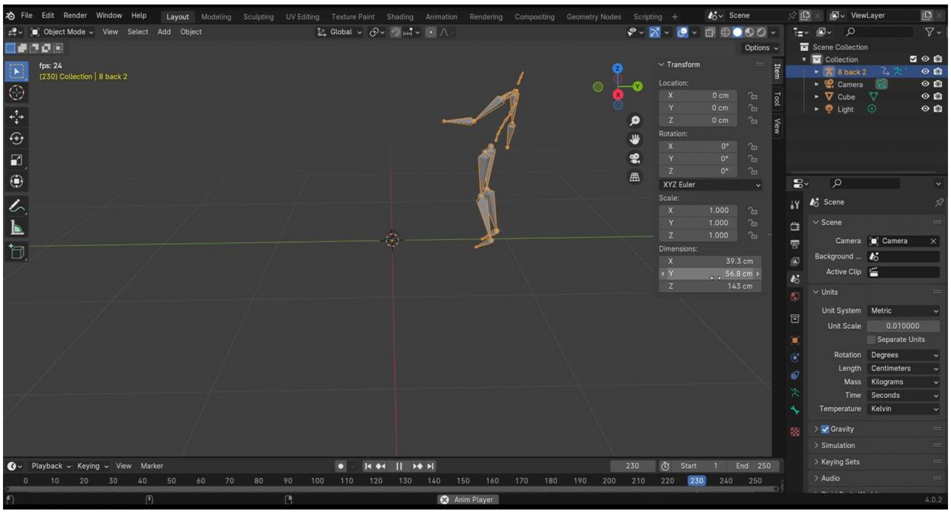
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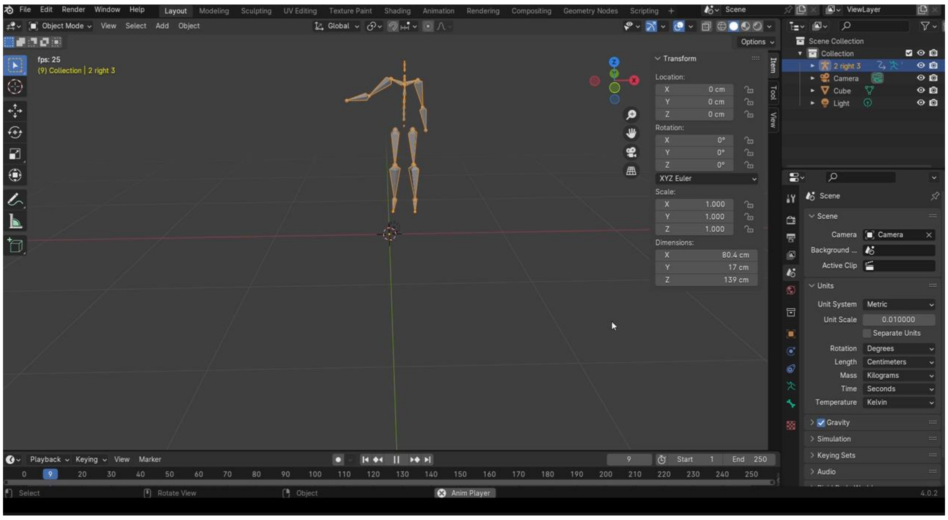
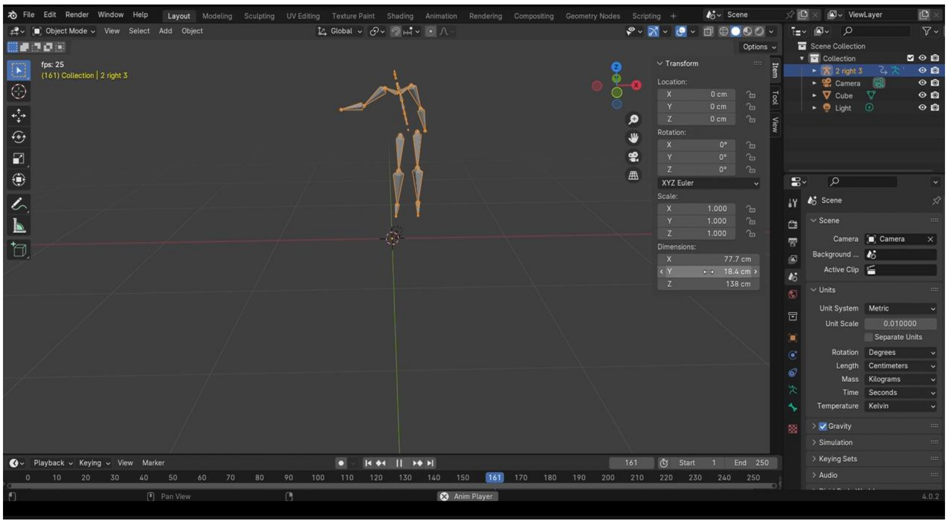
(230) Collection | 8 back 2





BVH files are transformed into Blender 4.0 App and sensor readings from the Y-axis are taken

APPENDIX K – TURNITIN REPORT

EXPLORING THE NOVEL SENSOR SYSTEM FOR DETECTING POSTURAL REACTIONS AMONG HEALTHY YOUNGER ADULTS: A PILOT STUDY

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