T.C.
BAHCESEHIR UNIVERSITY
GRADUATE SCHOOL
DEPARTMENT OF BIOMEDICAL ENGINEERING

EVALUATION OF THE PERFORMANCE OF PRESSURE MAPPING INSOLES FOR DIFFERENT TASKS AND DIFFERENT FOOTWEAR TYPES

MASTER'S THESIS

BARAN ARAS

ISTANBUL 2024

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THESIS ADVISOR

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ABSTRACT

TITLE OF THE THESIS

EVALUATION OF THE PERFORMANCE OF PRESSURE MAPPING INSOLES FOR DIFFERENT TASKS AND DIFFERENT FOOTWEAR TYPES

Baran, ARAS
Master’s Program in Bioengineering.
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Gait analysis is a critical tool for diagnosing diseases, evaluating outcomes, and developing management strategies. It is widely used in clinical practice and research to address human walking disabilities. Over recent decades, several indices have been developed to facilitate the assessment of gait by focusing on specific motion attributes. In clinical settings, gait analysis is often performed through visual observation, relying on the clinician’s experience. While modern technology offers advanced tools, visual assessment remains subjective and prone to variability. However, its simplicity and real-time application make it a practical choice for quick feedback in clinical environments.

Conversely, research employs quantitative gait analysis, offering precise and detailed insights into human walking. Parameters such as spatio-temporal measurements (e.g., step count and timing), ground reaction forces (GRF), joint kinematics, and energy expenditure enable the creation of comprehensive gait profiles. These profiles aid in identifying abnormalities and evaluating interventions.

Integrating qualitative and quantitative approaches combines the clinician's observational perspective with the researcher’s objective analysis. This synergy enhances patient care and deepens understanding of human movement.

Key Words: Forceplate, Pedar, Biomechanics, Ground Force Reaction, Statistical Parametric Mapping

ÖZET

FARKLI HAREKETLER VE FARKLI AYAKKABI TİPLERİ İÇİN BASINÇ HARİTALAMA TABANLIKLARININ PERFORMANSININ DEĞERLENDİRİLMESİ

Baran, ARAS
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Yürüme analizi, hastalıkların teşhisinde, sonuçların değerlendirilmesinde ve yönetim stratejilerinin geliştirilmesinde kritik bir araçtır. İnsan yürüme bozukluklarını ele almak için klinik uygulamalarda ve araştırmalarda yaygın olarak kullanılmaktadır. Son birkaç on yılda, yürüme analizini kolaylaştırmak ve belirli hareket özelliklerine odaklanmak amacıyla çeşitli indeksler geliştirilmiştir.

Klinik ortamlarda, yürüme analizi genellikle görsel gözlem yoluyla, klinisyenin deneyimine dayanarak gerçekleştirilir. Modern teknoloji gelişmiş araçlar sunsa da, görsel değerlendirme öznel olup değişkenlik gösterebilir. Bununla birlikte, basitliği ve gerçek zamanlı uygulanabilirliği sayesinde klinik ortamlarda hızlı geri bildirim için pratik bir seçimdir.

Buna karşın, araştırmalar, insan yürüyüşü hakkında kesin ve detaylı bilgiler sunan nicel yürüme analizini kullanır. Adım sayısı ve süresi gibi mekansal-zamansal ölçümler, yere reaksiyon kuvvetleri (GRF), eklem kinematiği ve enerji harcaması gibi parametreler, kapsamlı yürüme profilleri oluşturulmasını sağlar. Bu profiller, anormalliklerin belirlenmesine ve müdahalelerin değerlendirilmesine yardımcı olur.

Nitel ve nicel yaklaşımların birleştirilmesi, klinisyenin gözlemsel bakış açısını araştırmacının nesnel analiziyle birleştirir. Bu sinerji, hem hasta bakımını geliştirir hem de insan hareketi hakkındaki anlayışımızı derinleştirir.

Anahtar Kelimeler: Kuvvet Platformu, Pedar, Zemin Tepki Kuvveti, Basınç Merkezi, İstatiksel Parametrik Haritalandırma.

To my beloved family. Your expectations have become a reality.

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Chapter 1

Introduction

Gait analysis is an essential tool in the diagnosis, prognosis, and treatment planning of a wide range of pathologies. While being widely used in clinical or research environments to analyze the vastness of human gait impairments. Over the last decades, a large range of parameters have been made up to visualize and deal with human gait explaining different features of movement.

Gait analysis is typically done in the clinic by using basic gait observation. Although current technology has an intricate arsenal for gait analysis, clinicians nonetheless often use their acquired knowledge and years of experience to give assessments about a patient's walk. On the other hand, this way is naturally subjective. Clinicians interpret meaning out of an observable event based on what they know in their minds and the nature by which a clinician interprets events leads to different diagnoses or plans for management. Despite its subjectivity, clinician observational gait analysis continues to be the primary means of assessing walking ability due to it being practical and easy. Real-time gait evaluation without cumbersome equipment enables rapid assessments and instant feedback, which is especially helpful in a clinical setting that demands efficiency.

In contrast, research settings also study gait but use a more quantitative methodology, utilizing many parameters to describe the human gait pattern in an all-round and objective manner. These parameters include spatio-temporal measurements of steps quantifying the space and time of every step that a patient makes; ground reaction forces quantifying the impact of each step; kinematics of joints describing the movement of joints during walking; and energy expenditure estimating the efficiency of gait. This allows for detailed profiling of gait patterns, the identification of abnormalities, and the assessment of the effectiveness of different interventions on various pathologies.

An integrated approach of qualitative and quantitative data collection methods in gait analysis provides an upper hand in complementing the perspective that both clinicians and researchers who conduct gait analysis can achieve enhanced patient care and expanded knowledge about the movement of people [1-13].

1.1 Statement of the Problem

Force plates are considered to be the ‘’gold standard’’ of measuring ground reaction forces, and of assessing gait and balance, as in clinical and research settings. It is for these reasons that they are regarded to possess a high accuracy and dependability in sensing even momentary alteration of the load during exhaustive activities, essential in cross-checking and calibration of other pressure measurement tools including In-shoe pressure devices. Of all the available in-shoe systems, the most accurate and repeatable is the Pedar-X® system (Novel GmbH, Munich, Germany). Research has shown that, unlike some of the commercial units that were tested, Pedar® has zero deviation in mean-percentage error (MP) error average and low root-mean-square error (RMSE), providing solid pressure measurements. Other systems, for example, the Tekscan® system (Tekscan Inc., South Boston, MA, USA), have been seen to be less repeatable and more variable; therefore, they may not be as useful when it comes to analyzing pressure distribution [14-16]. Based on these points of view, we decided on the use of Pedar® and Bertec® force plate systems to investigate pressure and forces in our study because they are the most accurate systems among similar equipment.

1.2 Purpose of The Study

Force plates, even though precise, giving GRF precise interpretations, and being labeled as the gold standard, are inhibitive in the number of plates available discouraging a high number of step recordings per given session. This can become a real issue when attempting to gain either a broadband or full picture view of gait or a subject moving in some form of motion over a longer distance of area. Compared to this, the possibilities provided by the sensor insoles are more practical and suitable for long-term data recording. These insoles can be used both with an emphasis on laboratory conditions and in practical conditions, limiting the choice of insoles’ usage almost to none. They can thus be used in many contexts and it is thus possible to record data during predefined motion, as well as during more dynamic motion such as walking, running, or indeed any other motion. Furthermore, the sensor insoles are accurate in time, force, and balance, they are flexible and mobile, making them good tools for investigating temporal, force, and balance parameters. The versatility of such a sensor insole makes it an ideal tool in clinical or research settings where full, flexible biometric tracking is necessary. [17].

Chapter 2

Literature Review

In the study reported here, the Pedar® system, developed by Novel GmbH (Munich, Germany), one of the oldest and most established systems in the field of gait analysis and pressure measurements was used. In its original guise, this technology was presented as a means of evaluating pressure distribution over the foot and has been widely applied in clinical and research practice. The system aims to measure plantar pressure accurately while walking, running, and standing still. It was created as a transportable, convenient method of testing the mechanics and pathology of foot and gait [18].

Since the initial inception of the Pedar® system, several iterations with improvements in sensor capabilities and data analysis techniques have followed. Prior works employing the Pedar® system investigated pressure distribution in the sole during the stance phase of gait in diabetic and/or rheumatoid patients. Of Critical Importance has been its ability to record real-time data across its plantar surface using multiple sensors to diagnose and monitor conditions affecting foot mechanics and gait [19-20].

2.1 Precision and Reliability between Pedar and Force Plate

For further study of the Pedar® pressure-measuring insoles, previous research has looked at its ability to measure pressure in comparison to force platforms while undertaking walking activities. In one study, Barnett and colleagues tested these insoles by having participants walk over a force platform under two conditions: Inside shoes (shod condition), the insoles were located while taping the foot as if one is walking barefoot. The outcomes showed that the stance time was measured with reliability by the Pedar® insoles while the force values were measured lower than those of the force platform [21-22].

This point demonstrates that even though the insoles that have advanced as Pedar® can measure specific gait factors for instance the stance time, the ground reaction forces though measurable are measured with lower precision than Force platforms. This might be so since the insoles are placed inside the shoe, and in this respect, they may in one way or another influence the conclusions reached. This is to a similar effect as in arguing that Pedar® insoles could not be precise enough to resolve between individual ground reaction forces in any examination of gait. Here, the present study highlights some of the weaknesses in particular the fact that pressure-measuring insoles are not a total substitute for the Force Platform on force measurements especially in clinical or research on biomechanics [21-22].

2.2 Force Plate Technology

2.2.1 In-depth exploration of force plate technology and its applications. Force plates are historical instruments in biomechanics, sports science as well as rehabilitation. It is still unclear who first thought of constructing force plates, On the other hand, the use of force plates can be traced back to the early twentieth century. At first, they were crude, such devices being little more than mechanical assemblies that would attempt to measure the vertical loads during walking or running. The first major development in the process was made in the 1930s when engineers started applying strain gauges and several other types of sensors to enhance the level of the force measurements. The initial force plates were mainly used in laboratories for biomechanics, with special emphasis on gait analysis [23]. In the 1960s and 1970s, force plates' usage developed in fields such as sports science and clinical biomechanics. Multi-axis force plates available since then which can record the forces in more than one plane brought more elaborate information about the Ground Reaction Forces during different activities. It also witnessed a higher level of assessment techniques to evaluate movement and joint load analyses, which are a quality value-added proposition for researchers and clinicians alike [23]. By the end of the 1980's and the beginning of the 1990s force plates have become instrumental assess for the assessment of athletic performance and injury treatment. In connection with their use in sports, it was possible to define an athlete's strength, power, and balance, which were critical for training and rehabilitation. Today, force plates are a core tool in sports science and rehabilitation; though the technology still develops in leaps and bounds with improved sensors and better ways of analyzing the collected data, they are easily affordable and much more portable compared to their earlier models [23].

Force plates are an important tool in the actual rehabilitation of an athlete: there is often a need for accurate, measurable ground reaction forces and movement patterns. Far from being strictly used for evaluation, these tools are an anatomy that cannot be overemphasized in the assessment of rehabilitation, direction of treatment, and assessment of overall health in athletes. Perhaps the biggest strength of force plates is that they present information on multi-joint measures. Force plates facilitate the assessment of loads, strength, and power generation in lower limbs for providing vast knowledge about the physical capacity of the athlete which is essential to designing the rehabilitation programs and the augmentation of athletic performance. [24].

2.3 Previous Validation Studies Involving Force Plate

Plantar pressure is an essential tool for examining the forces applied in appropriate foot structures and gait analysis to determine the pressure over the foot during certain activities. The F-Scan system (Tekscan Inc., South Boston, MA, USA) is one of the most widely applied methods to assess in-shoe plantar pressure. On the other hand, criticisms have been made regarding the actual effectiveness of force measurements from the F-Scan, more so when the foot skeleton is in use for a long time and during dynamic actions such as walking.

An investigation was also made on the change in plantar pressure and temperature with time while using the F-Scan system. In the present investigation, a single subject was attached with two F-Scan sensors, one placed on the right foot and the other on the left foot. Initially, to enhance the first trial accuracy, step calibration was done before onset of the trials. The participant was then subjected to single-leg standing trials on a force plate (Bertec®, Columbus, OH, USA) that acted as the control for force values. After the standing trials, the participant was asked to perform a series of multiple level-ground walking trials while plantar pressure data was being captured.

The procedure was developed in such a way that involved taking measurements at specific time intervals to capture the temporal changes in the F-Scan system (Tekscan Inc., South Boston, MA, USA) sensor readings, and the whole procedure lasted 140 minutes. The participant repeated the walking trials every 10 minutes; the sensors' temperatures were taken right after the trials. Total force values obtained by the F-Scan system were reduced across trials, and for the two push modes analyzed, the decrease was most notable during the initial 60 minutes of the trials. This decay of force measurement makes it possible to conclude that the F-Scan sensors lose sensitivity or their calibration gets off during prolonged use, which in turn means that the information obtained with the help of F-Scan sensors over long periods does not remain accurate.

The other findings arising from the study include the changes in force measurements, where the force measurements of the two sensors increased during the initial hour of testing, and the changes in sensor temperature, where the temperature of the sensors increased. After this period, the temperature was relatively constant, thus agreeing with our view that the sensors could attain some point of thermal stability after using them for some time. Despite the increase in force and decrease in temperature during the 140 minutes, the center of pressure trajectories was stable. It appears that while the reduction in peak force values might occur, the relative loading distribution across the foot area was maintained. This therefore brings to light an interesting limitation of the F-Scan system for long-term dynamic studies [25].

A further study attempted to establish the level of correlation between the vertical forces detected by the MatScan pressure mapping system (Tekscan Inc., South Boston, MA, USA) and the forces recorded by an AMTI force plate (Advanced Mechanical Technology Inc., Watertown, MA, USA). The study aimed to measure the validity and reliability of the MatScan compared to the force plate and to compare any differences in force measurement between the two modalities.

Three participants were allowed to undertake the study, and each of them was challenged to undertake ten walking trials at a pace that was comfortable to him or her. The trials included a touchdown on the MatScan and the force plate. All the MatScan readings taken for the participants were taken after the participant's weight had been measured and documented to calibrate the equipment. Both systems recorded measurements simultaneously, and the mean and normalized values of these measurements were calculated with reference to the stance phase.

The findings of the present study were that the MatScan grossly overestimated the vertical forces concerning the AMTI force plate (Advanced Mechanical Technology Inc., Watertown, MA, USA). More precisely, the mean absolute difference in force measurements between the two systems was equal to 12.7%. Even though the trends are rather similar, the fact that the absolute values differ so dramatically indicates that the force values recorded by the MatScan may not be as accurate as those of the AMTI force plate, perhaps because of differences in calibration or because the encasing of the MatScan influences force measurements. The work done by the authors is a platform for further studies to fine-tune the accuracy of the MatScan system [26].

Additionally, another study was undertaken with the overall purpose of determining and comparing the precision of Center of Pressure (CoP) measurements between two devices: the Kistler force platform (Kistler Instrument Corp., Winterthur, Switzerland) and the Medilogic pressure-measuring insoles (Medilogic GmbH, Schönefeld, Germany). This comparison was done to overcome some of the drawbacks of previous studies, which used small samples or inadequate inclusion of various sizes of feet.

This was done by recording the CoP data of 65 participants while wearing pressure-measuring insoles in 6 different sizes. The study examined onset force thresholds and precise segment length thresholds for CoP path length and width measurement while participants walked over force platforms; these insoles were worn in socks.

Correlations between the two measurement systems were significant at a mean difference of 4.12% and a correlation coefficient of 0.74 for the CoP path length. The obtained data from the Kistler force platform and Medilogic insoles are equally effective in obtaining the length of the CoP path, which suggests. The correlation between the CoP path width and the width of the track providing the CoP motion was poor, with a mean difference of 7.04% (mean difference) and a low coefficient of 0.11. The reason for this, according to them, was the small number of sensors across the width of the insoles. Therefore, the study suggests that in measuring the length of the CoP path, the two sensors used measurements performed the same equally well; however, the placement of the sensors in the 5 and 7 sensor groups impacted the assessment of path width [27].

2.4 Pedar Systems Technology

Insoles containing pressure sensors arranged in insoles, which are inserted into footwear, are used with the Pedar® system (Novel GmbH, Munich, Germany). The system records pressure distribution over the sole during dynamic movements such as walking or during the stance phase of quiet standing.

The pressure sensors at the center of Pedar’s function can feed high-resolution readings back, yielding multiple points of pressure on the foot. The sensors track the patient’s movement as they apply pressure at different points to work out what is causing the pain. The data is then sent to a connected computer system where it is interpreted (along with the use of dedicated software). Each Pedar® system uses software that can analyze large datasets and online and offline analyses. This analysis yields a pressure map in color where areas of pressure on the foot are provided. Clinicians utilize such maps, and other graphical data, to identify locales of concern, (regions of high pressure likely to become material for ulcers or other foot complications).

The comparative analysis feature is one of the key functions that the Pedar has. A comparison of pressure data from one session can be made to see if the treatment is working or whether a condition is getting worse. Additionally, his software interfaces with video data, so that pressure data can be correlated to video recordings and visible patterns of movement. Because of its versatility, the Pedar® system can also be seamlessly incorporated into the wider clinical setting. For example, it can be connected to the systems EMED® (Novel GmbH, Munich, Germany) and Pliance® (Novel GmbH, Munich, Germany), which are also employed to assess pressure distribution in other parts of the body. This integration gives you a more complete picture of a patient than it does, just feet.

Finally, using Pedar® technology gives important measures for the evaluation of foot disorders and consequences, and also it defines the intervention strategies focused on individualized needs [28].

Chapter 3

Methodology

3.1 Participants

14 healthy young adults (2 males with an average weight of 80±5 kg and 12 females with an average weight of 65±3) with a mean age of 23±3 years. In terms of self-reported injury, none of the participants had sustained any injury. The research was cleared by the Research and Publication Ethics Board of Bahcesehir University and was done at the Biomedical Engineering Laboratory, Istanbul which is provided by the university. The overall ethical considerations of the study followed the tenets of the Helsinki Declaration in as much as respect for the dignity of the participants and their welfare was concerned. Along with that, all of the participants signed the written informed consent that guarantees their voluntary participation in research.

3.2 Experimental Setup and Data Collection

Participants who were carefully selected for the tasks were provided with Pedar® insoles (Novel GmbH, Munich, Germany) of an appropriate size for the implementation of the study before the start of the experiment. Subjects were asked to place their feet on the insoles parallely on the heels proceeding toward the toes. A battery pack was wrapped around the belt of their clothes and linked to the insoles through the cables. As it has already been stated following the manufacturers' recommendations a zero setting was made. The subjects then stepped on the force plate and the experiment began.

Holding insoles with double-sided tape, they were required to perform a host of activities. The tasks included performing squats and swaying in two directions: The sagittal plane direction is termed mediolateral (ML) and anteroposterior (AP). Each task was performed in three trials, with each trial consisting of three repetitions. The data generated from these tasks were video recorded, and the digital data were processed and analyzed using MATLAB® (MathWorks, Natick, MA, USA). Pre-treatment of the Pedar insoles was conducted to calibrate the device before every trial was conducted to ensure accuracy.

3.3 Data Processing

After all the data for the research study was collected, it was analyzed using MATLAB® R2024a software (The MathWorks, Inc., Natick, MA, USA). The first part of preparing the data obtained involved the cleaning and refining of the collected datasets for one additional step of analysis. Some pre-processing at the data level included filtering the signals from both datasets using a fourth-order Butterworth low-pass filter with a cut-off frequency of 10Hz. Using this technique reduced the challenge of high-frequency noise by only isolating the useful frequency band for further evaluation.

To address differences in sampling rates between the force plate and the Pedar® insoles, the force plate data, which was collected at a lower frequency, was smoothed and resampled to match the 100 Hz frequency used by the Pedar® insoles. This interpolation step was crucial for harmonizing the two datasets, ensuring they were comparable and suitable for meaningful statistical analysis.

Some problems were found, such as the absence of a synchronization device, on which is based the correspondence of the data streams generated by various sources. To combat this problem, a three-tap process was implemented during the input of the data. This method was suitable for recognizing the onset of a new force to complete the data registration procedure of the force plate and Pedar® insoles. No specific synchronization device was utilized but the three-tap technique proved to be a reasonably accurate method to align data post-collection.

The next stage was then the identification of the required indicators from the datasets, after synchronizing and preparing the data. CoP and vertical ground reaction force (Fz) were computed for force plate data. They are considered essential for force distribution and rate analysis in the course of the experimental tasks.

Specifically, for the Pedar® insoles, emphasis was placed on computing all the forces acting on the right insole, the left insole, and both insoles simultaneously. These gave a clear picture of force distribution as compared to that that the insoles were recording via the plates. The study applied the forces measured by each insole separately and then combined these values to confirm that the Pedar® insoles' measurements provided a comprehensive comparison with the force plate data. The systematic approach to data collection, timing, and analysis ensured high levels of confidence in the results and highlighted the efficacy of the Pedar® insoles in relation to the force plate. The techniques employed not only facilitated effective analysis of the datasets but also demonstrated the feasibility of implementing complex methodological solutions to address challenges, such as the absence of synchronization devices in experimental methodologies.

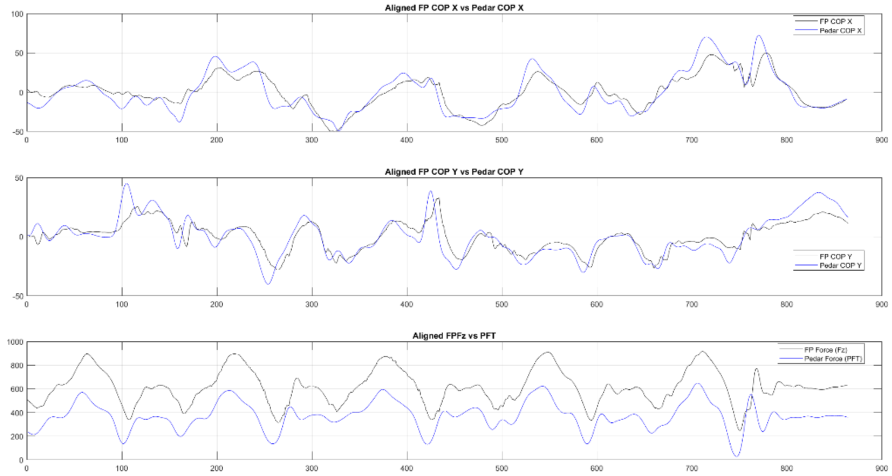

Figure 1. The plot of synchronized and aligned CoPx, CoPy, and Fz of Pedarx vs Force plate for squat task

3.4 Statistical Analysis

For the assessment of the error variations for CoPx, and CoPy in AP and ML coordinates, the RMSD values were calculated. Error variation connected with the Fz was also assessed. For the determination of the normality of the distribution of the RMSD values, the Shapiro-Wilk test was employed. In this case, data that were distributed non-parametrically were analyzed using the Friedman test; the Wilcoxon Signed-Rank test was used for post hoc analysis. Statistical significance was set at p < 0. 05. Finally, Statistical Parametric Mapping (SPM) analysis was used for visualization between the two recording systems. Among the statistical tools used, SPSS software (IBM ® SPSS ® Statistics 25) developed by IBM Corp. in the USA was applied.

Chapter 4

Findings

The study presented in this chapter aimed to evaluate and compare the parameters derived from the Pedar® system and the force platform system, the latter widely recognized as the gold standard for assessing structural balance. Measurements were conducted under four distinct conditions:

Barefoot, where participants performed tasks without any footwear.

Wearing socks, to analyze minimal cushioning or support.

Wearing flat shoes, which offer basic support without specialized design for dynamic balance.

Wearing sneakers, which typically provide advanced cushioning and structural support designed for stability and impact absorption

In Ground Force Reaction (GFR) analysis, the average error of ground reaction force (Fz), the standard deviation of ground reaction force (Fz), mean horizontal displacement of the center of pressure (COD), range of ground reaction force (Fz) variability has been estimated. The emphasis of this thesis was on the mean error in ground reaction force (GRF) between the force plate and Pedar® systems. Statistical analyses were performed to evaluate and compare agreement between these two methods under each experimental condition, with $p < 0.05$.

4.1 Results

This section presents the synthesis of the obtained results for the CoP and GFR values for every task accomplished by subjects. To help understand the results of the analysis, the RMSE values have been plotted against the values from the force plate and the devices Pedar and the force plate with the outcomes of the statistical tests from the preceding section involving Statistical Parametric Mapping (SPM) analysis.

4.1.1 Rmse results. The RMSE values in Table 1, Table 2, and Table 3 highlight the discrepancies between the Pedar system and the force plate across all tasks. RMSE values were calculated for the (CoP) along the x-axis (CoPx) and y-axis (CoPy) as well as the vertical ground reaction force (Fz).

RMSE results shown in Table 1 ranged between 1.9±11.25 mm and 35.7±11.25 mm for barefoot, 5.9±1.6 mm and 27.7±1.6 mm for flat shoes, 5.5±13.25 mm and 47.4±13.25 mm for sneakers, 6.13±16.58 mm and 55.29±16.58 mm for socks along the anteroposterior (AP) or x-direction.

Table 1

The Rmses Of The Cop Estimations For The Ap Sway Task For All Subjects Along The X Y And Z Axes, According To Each Footwear In Addition To The Mean And Standard Deviation Values Of The Total Rmses Of All Subjects

	BAREFOOT			FLAT SHOE			SNEAKERS			SOCKS		
ID	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**
1	9,09	4,75	169,7	5,99	2,06	68,96	10,29	3,05	60,57	6,26	5,01	130,3
2	8,57	3,11	33,72	17,53	2,58	89,02	17,03	3,24	116,3	9,59	5,66	72,44
3	35,71	8,91	170,6	8,08	3,4	33,36	6,77	2,53	28,27	52,66	7,8	138,6
4	2,56	1,43	98,75	9,16	1,63	131,1	21,49	5,88	370,4	19,59	3,52	37,95
5	7,69	2,88	31,35	24,55	6,13	172,1	14,96	4,46	199,8	7,72	2,12	35,22
6	6,52	3,21	57,64	8,28	4,38	225,5	49,09	6,65	187,5	7,33	2,65	54,07
7	8,82	2,57	38,37	13,45	3,03	121,3	18,85	4	336,5	22,79	4,16	39,57
8	9,32	4,45	206,5	4,57	2,27	82,44	9,5	2,68	46,18	7,69	6,03	162,1
9	9,54	3,79	36,56	21,51	2,77	104,8	13,56	2,44	126,3	10,17	6,23	57,59
10	37,08	10,38	145,6	7,8	3,49	31,73	5,58	2,57	33,04	55,3	8,68	126,2
11	1,95	1,68	106,3	11,27	1,4	119,2	18,25	5,23	457,7	16,38	3,04	38,17
12	7,49	2,7	24,64	27,77	6,97	181,4	16,25	5,45	155,5	6,14	2,2	27,48
13	7	3,36	54,95	6,24	3,79	271,8	47,41	8	182,8	6,43	3,06	60,17
14	8,91	3,05	41,57	14,66	2,83	146,1	20,69	3,79	350,3	26,88	3,96	40,69
Mean	11,6	4,02	86,89	12,92	3,34	127,1	19,26	4,28	189,3	18,21	4,58	72,92
SD	11,25	2,57	62,5	7,37	1,6	68,68	13,23	1,74	138,8	16,58	2,07	45,79

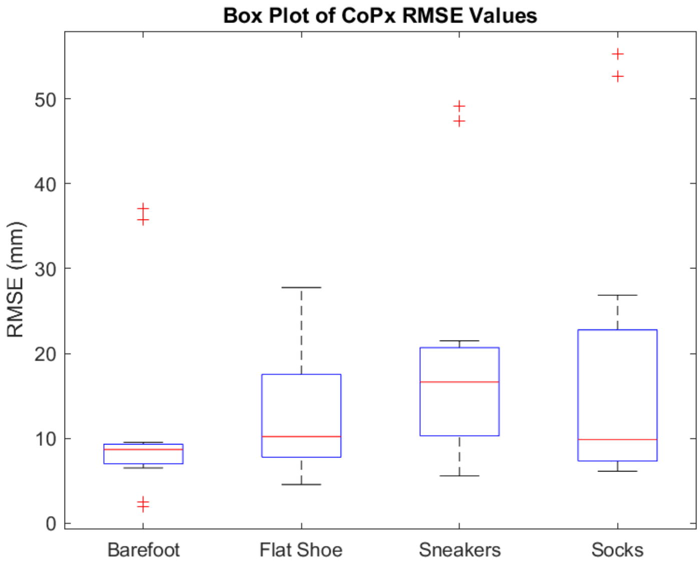

Figure 2. Box plot of CoPx RMSE values for the AP sway task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

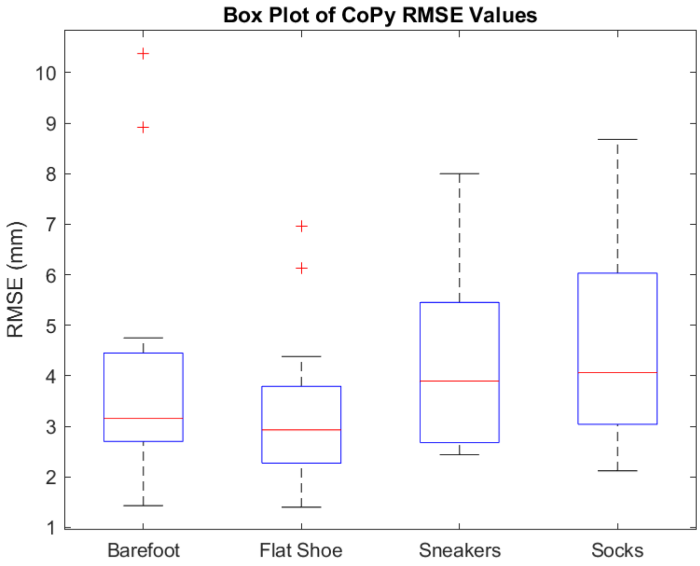

Figure 3. Box plot of CoPy RMSE values for the AP sway task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

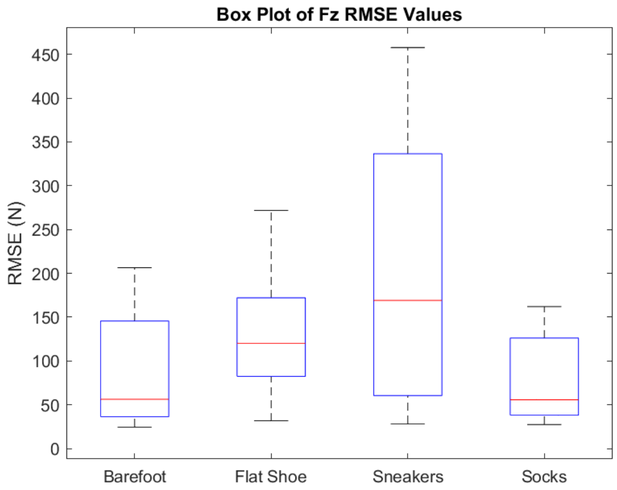

Figure 4. Box plot of Fz RMSE values for the AP sway task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

RMSE results shown in Table 2 ranged between 5.37±8.04 mm and 30.9±8.04 mm for barefoot, 5.87±10.33 mm and 39.8±10.33 mm for flat shoes, 8.78±2.8 mm and 106.47±2.8 mm for sneakers, 5.55±1.5 mm and 40.64±1.5 mm for socks along the mediolateral (ML) or y-direction.

Table 2

The Rmses Of The Cop Estimations For The Ml Sway Task For All Subjects Along The X Y And Z Axes, According To Each Footwear In Addition To The Mean And Standard Deviation Values Of The Total Rmses Of All Subjects

	BAREFOOT			FLAT SHOE			SNEAKERS			SOCKS		
ID	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**
1	3,96	7,11	137,5	2,67	10,98	36,52	4,34	18,76	40,95	4,03	8,9	142,1
2	5,93	8,22	121,3	6,34	22,76	47,34	10,28	85,88	101,1	3,21	9,32	121,9
3	5,22	10,42	148,2	3,27	5,92	71,73	2,98	15,01	25,8	4,39	6,28	141,3
4	3,77	20,25	53,88	4,42	39,88	115,8	7,71	31,99	311,6	4,89	40,16	24,46
5	6,4	28,25	36,33	9,55	33,47	133,5	5,74	13,54	123,1	4,37	16,37	46,36
6	2,21	6,43	20,48	4,57	10,92	257,2	9,66	10,43	251,9	2,05	12,46	72,02
7	1,98	9,89	41,28	3,91	18,99	73,31	6,04	32,72	392,9	6,54	37,22	36,99
8	4,62	5,38	142,3	3,43	12,92	31,32	4,74	14,61	37,71	4,09	7,16	127,3
9	4,85	8,38	151,4	4,45	19,97	57,24	11,41	106,4	123,0	3,74	7,5	143,3
10	4,07	8,31	152,1	3,57	5,88	56,7	3,2	13,39	24,39	5,18	5,56	170,4
11	2,99	16,67	54,3	4,64	26,04	112,5	8,58	33,51	276,2	5,6	40,65	26,16
12	5,33	30,1	33,25	10,23	28,18	95,34	5,38	16,67	101,7	3,97	20,24	40,69
13	2,01	7,59	19,76	3,03	10,15	248,5	10,05	8,79	238,9	2	13,78	57,21
14	1,79	12,24	41,11	4,39	16,93	73,77	4,88	27,7	368,3	7,36	33,72	43,24
Mean	3,94	12,81	82,39	4,9	18,79	100,7	6,78	6,79	172,8	4,37	4,39	85,23
SD	1,55	8,04	55,07	2,31	10,33	71,13	2,79	2,8	130,5	1,46	1,5	52,51

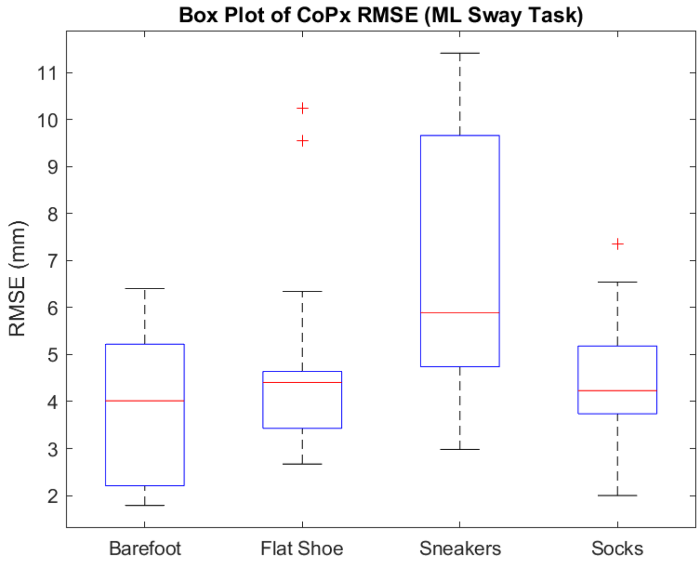

Figure 5. Box plot of CoPx RMSE values for the ML sway task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

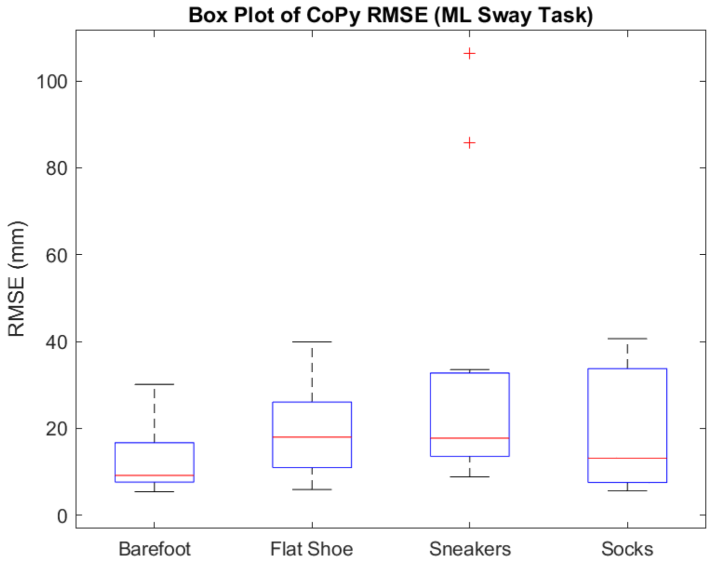

Figure 6. Box plot of CoPy RMSE values for the ML sway task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

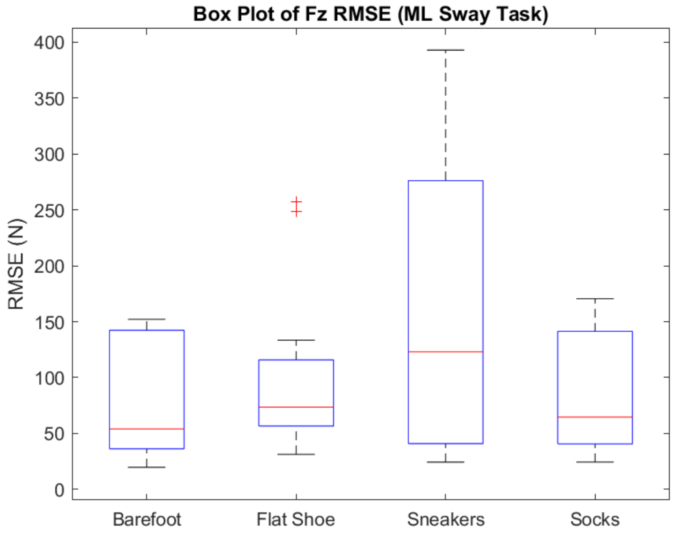

Figure 7. Box plot of Fz RMSE values for the ML sway task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

RMSE results shown in Table 3 ranged between 26.26±48.31 mm and 186.02±48.31 mm for barefoot, 38.1±74.98 mm and 259.18±74.98 mm for flat shoes, 26.52±95.95 mm and 341.74±95.95 mm for sneakers, 31.40±36.94 mm and 150.87±36.94 mm for socks along the vertical or z-direction.

Table 3

The Rmses Of The Cop Estimations For The Squat Task For All Subjects Along The X Y And Z Axes, According To Each Footwear In Addition To The Mean And Standard Deviation Values Of The Total Rmses Of All Subjects

	BAREFOOT			FLAT SHOE			SNEAKERS			SOCKS		
ID	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**	**COPX**	**COPY**	**FZ**
1	6,97	4,09	96,8	4,55	3,51	43,6	3,90	3,66	26,5	6,48	3,73	96,9
2	3,06	3,20	89,08	7,55	2,48	80,41	6,65	2,91	120,8	4,46	4,47	104,7
3	5,02	2,48	142,8	4,63	1,90	38,10	4,57	3,72	173,4	9,57	3,70	150,8
4	3,66	2,61	149,6	11,64	7,96	155,2	10,35	8,50	340,7	6,39	5,74	54,8
5	6,04	4,30	63,82	11,68	8,15	241,6	10,15	9,956	236,6	12,09	9,68	98,8
6	6,23	3,37	89,01	6,60	3,75	177,8	19,33	13,9	206,4	4,63	4,31	50,4
7	3,90	3,64	32,81	5,89	5,25	176,2	7,42	5,87	283,4	4,66	4,01	31,4
8	5,76	3,26	109,8	5,48	3,19	49,34	3,18	3,18	30,9	6,75	3,62	105,2
9	2,32	3,85	104,6	8,75	2,73	90,96	6,43	2,83	149,3	5,46	4,23	108,4
10	4,86	2,00	172,6	5,16	2,02	39,5	3,64	3,85	203,4	7,47	4,30	125,9
11	4,27	2,62	186,0	9,75	8,13	174,4	10,9	6,63	341,7	6,66	6,25	45,1
12	6,40	3,53	63,9	10,8	7,90	259,	7,67	9,93	210,5	10,7	8,27	97,7
13	6,29	3,47	78,8	5,57	3,35	144,3	20,04	14,8	231,9	5,38	3,92	60,8
14	4,60	2,74	26,2	4,42	5,26	176,6	8,49	5,05	246,1	3,94	3,27	32,2
Mean	4,96	3,22	100,4	7,32	4,69	131,9	8,77	6,78	200,1	6,77	4,96	83,1
SD	1,39	0,66	48,31	2,71	2,40	74,97	5,25	4,06	95,95	2,46	1,89	36,94

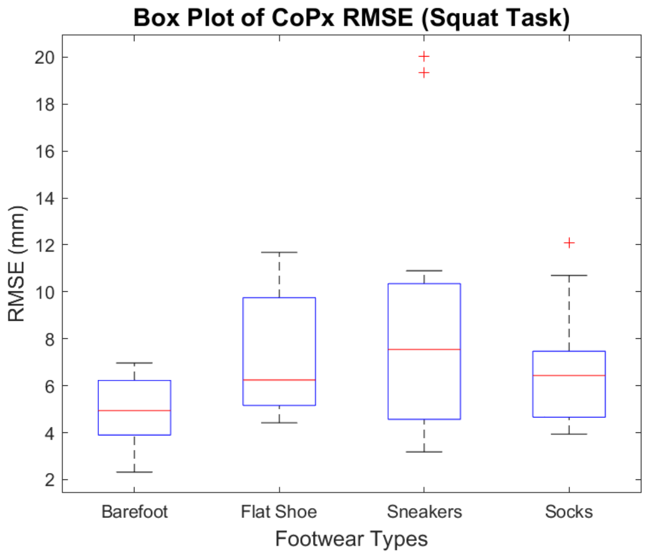

Figure 8. Box plot of CoPx RMSE values for the squat task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

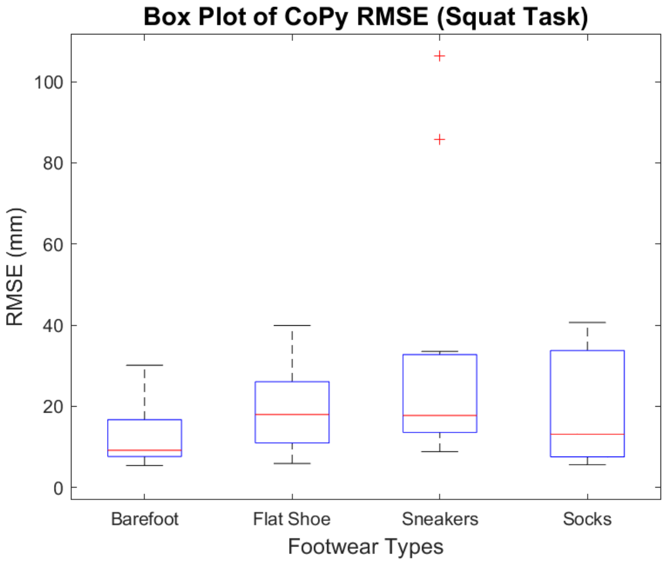

Figure 9. Box plot of CoPy RMSE values for the squat task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

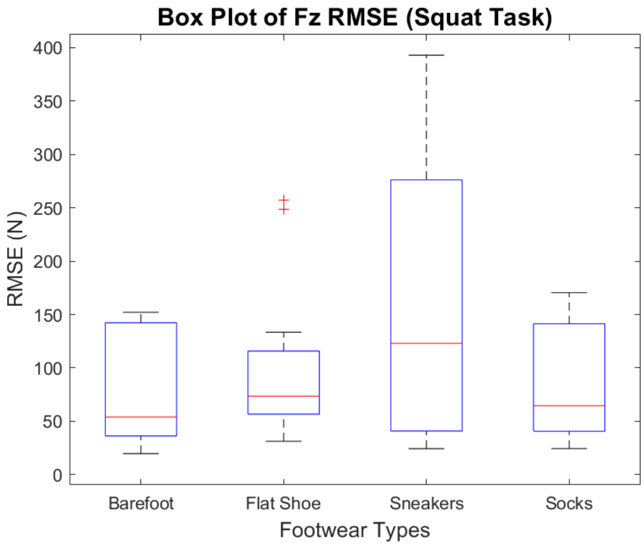

Figure 10. Box plot of Fz RMSE values for the squat task across different footwear types (Barefoot, Flat Shoe, Sneakers, and Socks). The RMSE values represent variability in the anterior-posterior center of pressure estimations.

4.2 AP Sway Analysis

This study aimed to evaluate the agreement between the Force Plate and Pedar® systems during the anterior-posterior (AP) task under four distinct footwear conditions: barefoot, flat shoe, sneakers, and socks. The analysis centered on three primary metrics: the center of pressure in the anterior-posterior direction (CoPx), the center of pressure in the medial-lateral direction (CoPy), and the vertical force (Fz). Figures 1, 2, and 3 present the Statistical Parametric Mapping (SPM) results for CoPx, CoPy, and Fz, respectively. SPM was employed to identify significant time intervals that indicated discrepancies between the measurements obtained from the two systems. These intervals provide insights into temporal differences in force and pressure dynamics, aiding in understanding the performance of each device. Below are the pre-processed data and SPM analysis results for the AP sway task.

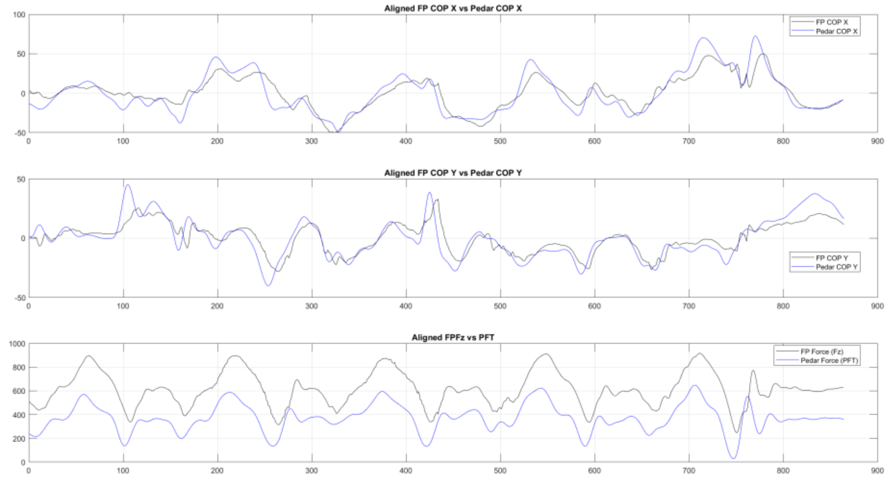

Figure 11. CoPx, CoPy, and Fz vs Total Force during the squat task for one subject

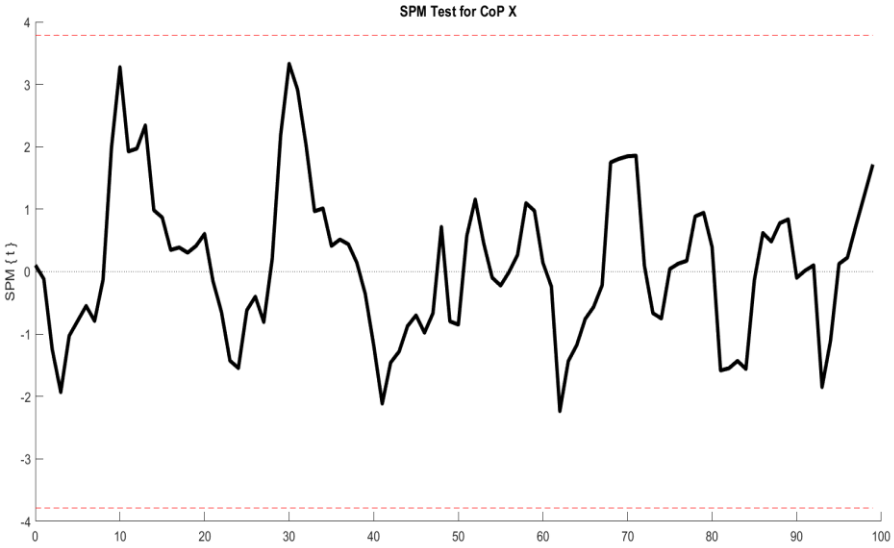

Figure 12. SPM Test for CoPx for all subjects wearing socks during AP Sway Task

Overall analysis showed that for CoPx sneakers showed the highest RMSE values in the x-axis (8.77±5.25), while barefoot demonstrated the lowest (4.96±1.39), indicating superior anteroposteriol stability.

4.2.1. Copy (anterior-posterior center of pressure). Barefoot: The anterior-posterior (AP) task was analyzed by evaluating the performance of the Pedar® system in comparison to the Bertec® Force Plate system across multiple time intervals. Significant differences were identified in the CoPx results, particularly under sneakers conditions. These discrepancies suggest potential limitations of the Pedar® system in accurately tracking AP center of pressure movements when structural absorption from footwear is too high. This may be due to the Pedar® system's reliance on external stabilization, which is overdone in sneakers scenarios where pressure distribution is less uniform and more variable. These findings emphasize the influence of footwear on the reliability of CoPx measurements and highlight the need for further improvements in the Pedar® system's sensitivity and accuracy to enhance its applicability in sneakers tasks.

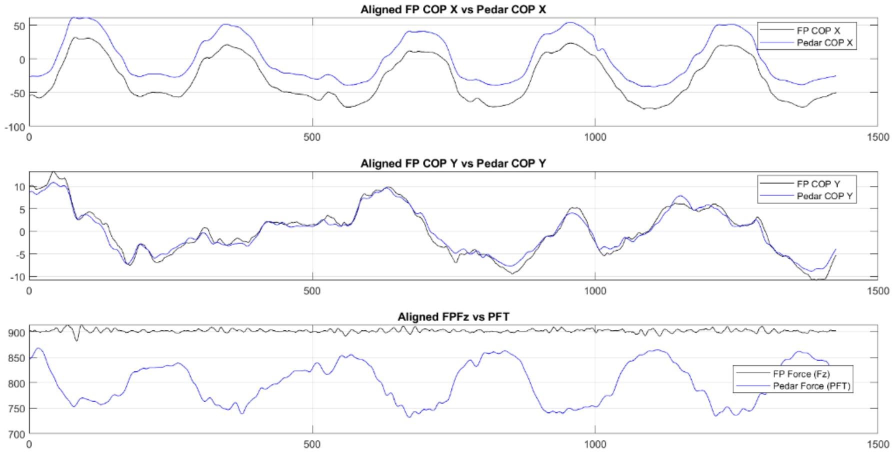

Figure 13. CoPx, CoPy, and Fz vs Total Force during AP sway task for one subject

Flat shoe: Using flat shoe conditions, the agreement between the Pedar® and Bertec® force plate systems was lesser than that for barefoot conditions. Analysis showed fewer frequent, less pronounced significant time intervals indicating that the structured sole from flat shoes aids stabilizing effects in the Pedar® sensor measurements and thus renders them more accurate.

Sneakers: The highest level of RMSE was found amongst footwear types for CoPx and maximal significant time intervals indicated discrepancies between Pedar®

and Bertec® Force Plate. This finding indicates that sneakers are less reliable in producing Pedar® measurements, most likely because the cushioning and homogeneous structure of these shoes reduce the stability and consistency of sensor data.

Socks: The agreement among the Pedar® and Bertec® Force Plate systems was moderate on the condition of the socks with some significant time intervals. The discrepancies, however, were larger than seen in barefoot conditions. In the absence of a structured sole in trial socks, there is less stability in Pedar® measurements.

4.2.2. Copx (medial-lateral center of pressure). Barefoot: Lateral pressure tracking of the Pedar® system during tasks performed without footwear revealed considerable discrepancies throughout the entire task duration, indicating substantial variability in the CoPy (center of pressure in the medial-lateral direction). This is likely due to the minimal containment of the sensors, which may have led to increased instability and reduced measurement accuracy.

Flat shoe: Under flat shoe conditions, CoPx (center of pressure in the anterior-posterior direction) demonstrated stronger agreement between the Pedar® and Bertec® Force Plate systems, with fewer significant intervals. This improvement is likely attributed to the structured sole of flat shoes, which helped stabilize medial-lateral pressure distribution and sensor alignment.

Sneakers: Sneakers consistently achieved the second highest agreement for CoPy measurements, with minimal significant time intervals. The superior fit and cushioning properties of sneakers likely contributed to their consistent performance by enhancing sensor stability and ensuring even pressure distribution across the sole.

Socks: Measurements of CoPy under sock conditions exhibited the lowest agreement for CoPy measurements, with minimal significant time intervals. With minimal structural support precise lateral pressure tracking, results in increased variability in the measurements.

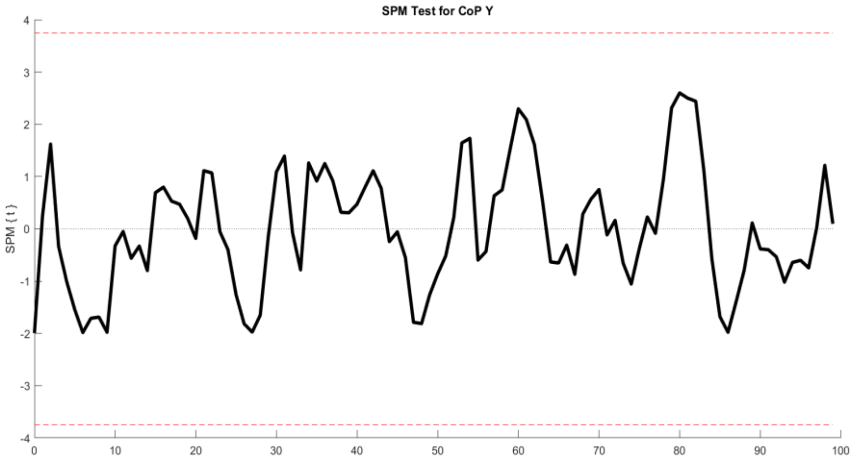

Figure 14. SPM Test for CoPy for all subjects wearing socks during AP Sway Task

Overall analysis showed that for CoPy socks showed the highest RMSE values in the y-axis (4.58±2.08), while flat shoes demonstrated the lowest (3.34±1.6), indicating superior mediolateral stability.

4.2.3. Fz (vertical force). Barefoot: Vertical force (Fz) discrepancies were significant across a substantial portion of the task duration, indicating potential limitations in the Pedar® system's force-sensing capabilities when used without a footwear interface. The lack of structural support under barefoot conditions likely exacerbates the variability in vertical force tracking.

Flat shoe: Vertical force agreement between the Pedar® and Bertec® Force Plate systems improved under flat shoe conditions, with fewer significant intervals observed. This finding supports the hypothesis that structured footwear enhances the Pedar® system's measurement accuracy by stabilizing force distribution.

Sneakers: Sneakers demonstrated the lowest agreement in vertical force (Fz) measurements, with almost maximum significant intervals. This result suggests that sneakers do not optimize the Pedar® system's ability to track vertical forces reliably, likely due to their cushioning and structural design, which demote consistent sensor performance.

Socks: Vertical force discrepancies were less frequent under sock conditions compared to other footwear. This condition exhibited the highest agreement, consistent with the findings.

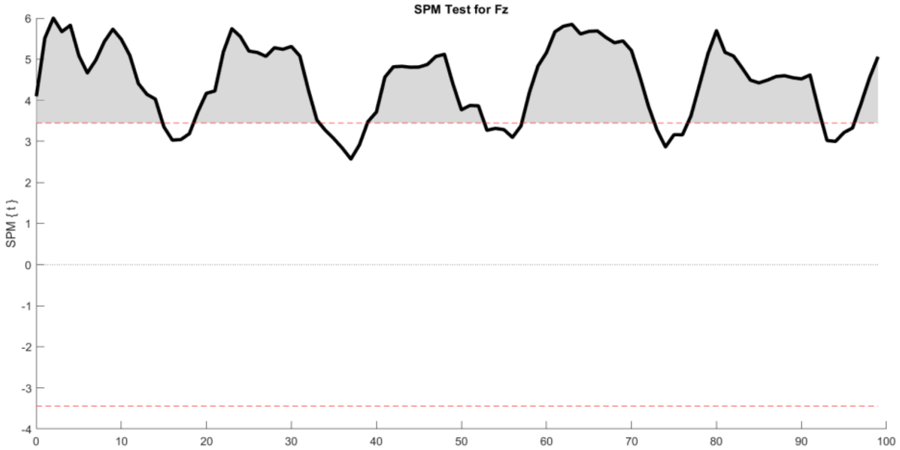

Figure 15. SPM Test for Fz for all subjects wearing socks during AP Sway Task

4.3 ML Sway Analysis

4.3.1 Center of pressure (cop) x-axis. The SPM analysis for the CoP in the X-axis across all footwear types demonstrated varying degrees of significant differences between the Pedar insole and the force plate. These differences reflect how each device measures medial-lateral shifts during the ML task.

Barefoot: Significant differences were observed during the early and mid-phases of the task. The Bertec® Force Plate captured larger CoP deviations, indicating that the Pedar® system may underestimate lateral shifts in the center of pressure without the stabilization provided by footwear. This finding highlights the challenges of accurate measurement in barefoot conditions, where sensor stability is limited.

Flat shoe: Differences between the Pedar® and Bertec® Force Plate systems were highest under flat shoe conditions, suggesting decreased alignment between the two devices.

Sneakers: Significant differences were primarily observed during the later phases of the task. This could be attributed to the cushioning effect of sneakers, which may redistribute force and subtly influence CoP readings. Nonetheless, sneakers demonstrated overall reliability in aligning with the force plate measurements across the task duration.

Socks: Significant deviations were observed throughout the task in sock conditions, likely due to reduced friction and the lack of structural support, which increase variability in CoP measurements. These findings suggest that socks do not provide sufficient stability for accurate lateral pressure tracking compared to footwear with more structured soles.

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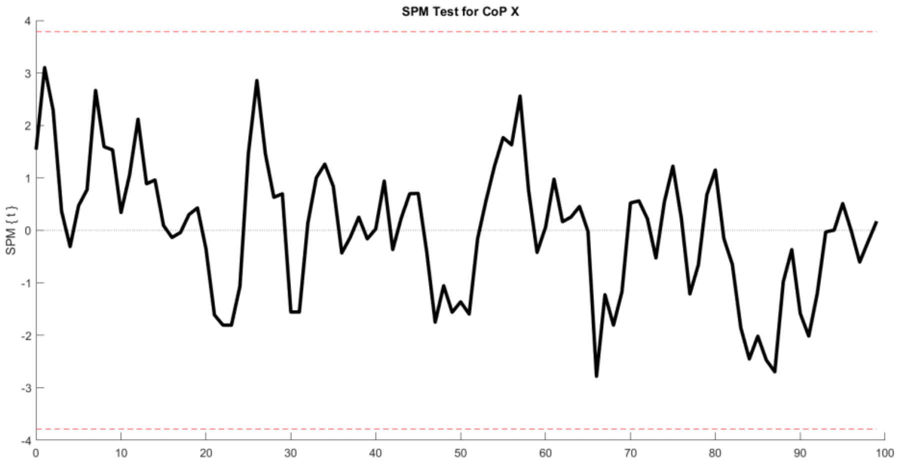

Figure 16. SPM Test for CoPx for all subjects wearing socks during ML Sway Task

4.3.2 Center of pressure (cop) y-axis. Barefoot: Significant differences were observed during the early and mid-phases of the task. The Bertec® Force Plate captured larger CoP deviations, indicating that the Pedar® system may underestimate lateral shifts in the center of pressure without the stabilization provided by footwear. This finding highlights the challenges of accurate measurement in barefoot conditions, where sensor stability is limited.

Flat shoe: The Pedar® and Bertec® Force Plate systems were found to have pronounced differences between the two systems under flat shoe conditions, indicating less agreement between the two devices. Indeed, reduced alignment is probably due to the surface offered by the flat footwear that produces less consistent sensor readings and maximizes measurement variability.

Sneakers: Differences primarily varied across later phases of the task. That’s something that sneaker cushioning could locally distribute force and hence subtly change CoP readings to account for. However, across task duration, sneakers were generally reliable at aligning with the force plate measurements.

Socks: However, sock conditions showed lesser significant deviations throughout the task because minimal structural support reduces the variability of CoPy measurements. They find that socks provide enough stability for evaluating lateral pressure tracking to levels of accuracy similar to that attained in footwear with more structured soles.

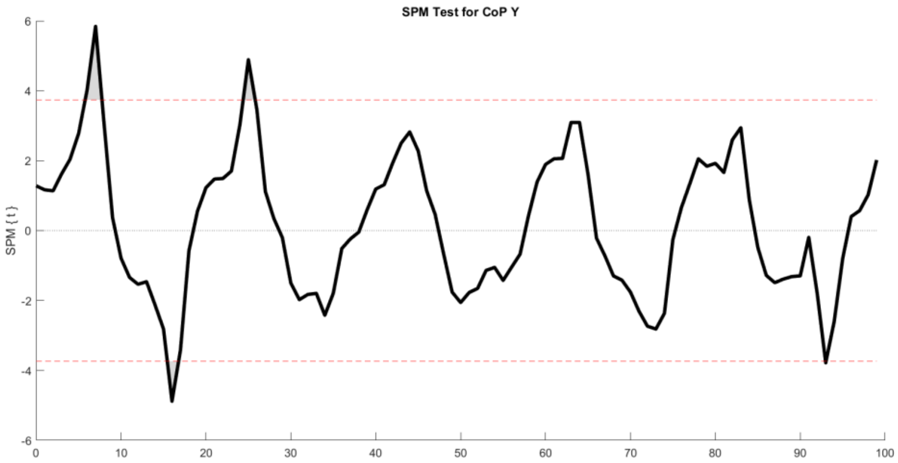

Figure 17. SPM Test for CoPy for all subjects wearing socks during ML Sway Task

4.3.3 Fz (vertical force). The vertical force (Fz) analysis demonstrated varying degrees of alignment between the Pedar® insole and the Bertec® Force Plate:

Barefoot: Differences were pronounced during the dynamic phases of the task. Such discrepancies indicate that vertical forces measured using the Pedar® system may be underestimated in the absence of footwear support. A stabilizing interface might enhance the reliability of force sensing, but the system may be vulnerable to reliability without structured footwear.

Flat shoe: We found minimal differences, meaning that flat footwear gives you a stable and uniform base. This stability increases the alignment of the two systems because the structured sole provides a constant pressure distribution and accurate readings for vertical force.

Sneakers: Intermittently significant deviations were observed, possibly as a result of the cushioning properties of sneakers. Sneakers do seem to improve comfort and spread forces more evenly, however, they may also alter the interaction between the foot and Pedar® sensors and thus cause variability in vertical force measurements.

Socks: The greatest differences were in the socks' condition, probably due to the lack of support structurally, and friction. These factors also add variability and increase measurement error regarding vertical force measurements, and such variability is a setback for the potential use of socks in tasks where precise force tracking is required.

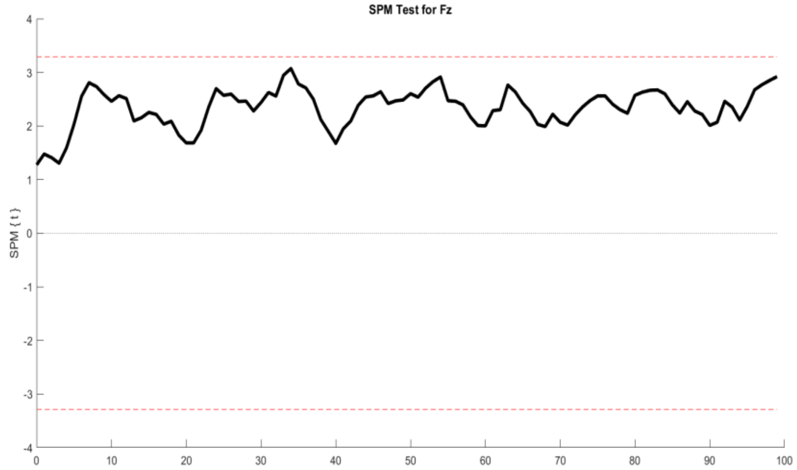

Figure 18. SPM Test for Fz for all subjects wearing socks during ML Sway Task

4.4 Squat Analysis

4.4.1 Center of pressure (cop) x-axis. The Center of Pressure (CoP) X-axis (anteroposterior, AP) analysis during the squat task (SQT) revealed significant differences across footwear types when comparing measurements from the Pedar® system and the Bertec® Force Plate. These differences highlight the influence of footwear on AP force transmission:

Barefoot: Significant discrepancies were observed less during the weight-shifting phases, particularly as participants transitioned between the eccentric (downward) and concentric (upward) phases. This indicates the Bertec® Force Plate and Pedar® systems are in agreement.

Flat Shoes: Discrepancies were smaller compared to barefoot conditions. The structured sole of flat shoes appeared to provide a more stable base, reducing variability in AP force measurements. This stabilization likely improved the alignment between the two systems during dynamic movements.

Sneakers: Significant differences were most prominent during the eccentric phase of the squat. The cushioning properties of sneakers, while beneficial for comfort and overall support, may have altered force transmission, leading to slight underestimations of AP forces by the Pedar® system.

Socks: Socks displayed the highest variability second to the sneakers, with significant differences noted during both the descent and ascent phases of the squat. The lack of structural support in socks likely contributed to inconsistent sensor stabilization, resulting in greater deviations in AP force measurements compared to other footwear types.

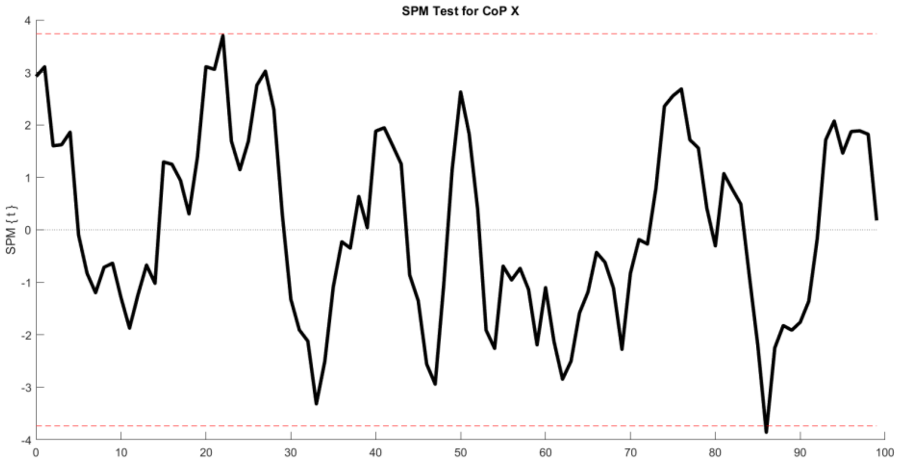

Figure 19. SPM Test for CoPx for all subjects wearing socks during Squat Task

4.4.2 Center of pressure (copy) y-axis. The Center of Pressure (CoP) Y-axis (mediolateral, ML) analysis during the squat task (SQT) highlighted differences across footwear types when comparing the Pedar® system and the Bertec® Force Plate. The findings revealed variability in force application and lateral pressure tracking based on footwear:

Barefoot: Barefoot conditions exhibited the lowest variability in CoP Y-axis measurements, particularly during the weight transition phases of the squat. SPM results indicated significant discrepancies in the early and mid-phases of the task, suggesting that the Pedar® system easily captures precise mediolateral shifts without the stabilizing support of footwear. This may result from increased sensor movement and reduced contact uniformity inherent to barefoot conditions.

Flat Shoes: Flat shoes demonstrated the second-best agreement between the Pedar® system and the Bertec® Force Plate. Discrepancies were smaller and less frequent, particularly during the ascent phase. The structured sole of flat shoes likely minimized lateral force variability, enabling more consistent CoP Y-axis measurements. SPM results supported this finding, with fewer significant time intervals than barefoot and socks.

Sneakers: Sneakers showed the biggest discrepancies in CoP Y-axis measurements, with significant time intervals primarily occurring in the later phases of the task. The cushioning and design of sneakers demoted consistent mediolateral force application, diminishing the Pedar® system's ability to align with the Force Plate. SPM analysis confirmed the low level of agreement, highlighting sneakers as the least stable footwear option for mediolateral force tracking during the squat task.

Socks: Similar to sneakers, socks showed notable variability, with significant time intervals observed throughout the dynamic phases of the squat. The absence of a structured sole contributed to reduced lateral force stabilization, particularly during transitions between descent and ascent. SPM analysis revealed discrepancies at critical force application points, reinforcing the challenges in maintaining consistent mediolateral measurements under this condition.

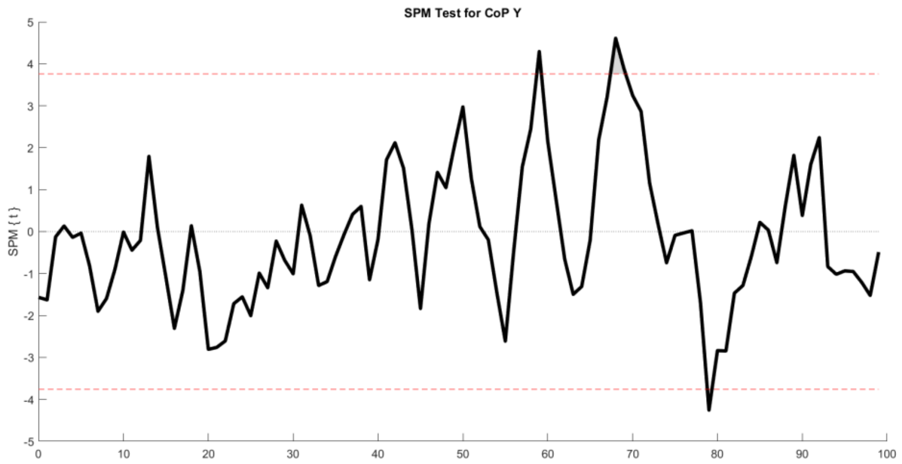

Figure 20. SPM Test for CoPy for all subjects wearing socks during Squat Task

4.4.3 Vertical force (fz). Vertical force analysis (Fz) for the squat task (SQT) showed distinct differences in the application of force from the Pedar® system vs Bertec® Force Plate for various footwear types. These differences provide valuable insights into how footwear impacts the stability and accuracy of vertical force measurements:

Barefoot: The second most variability was shown by vertical force measurements in barefoot conditions for high variability between the force application peak, contrary to footplate forces, at the lowest points of the squat. Unbalanced forces are thought to result from the lack of cushioning or structural support, resulting in a discrepancy between how feet functioned when stepping on the Pedar® system versus while stepping on the Force Plate. SPM results indicated significant time intervals for both the descent and ascent phases and indicated that limitations of the Pedar® system in barefoot conditions may not accurately capture vertical forces.

Flat Shoes: Squat variability was reduced for flat shoes as opposed to sneakers, with time points most significant in the concentric (upward) portion of the squat. The flat shoes' flat sole structures and uniformity may have contributed to the more stable (and thus more consistent) Pedar® system vertical forces. In this condition, we had fewer significant intervals, meaning that there was more alignment between the two systems than when testing with the sneakers.

Sneakers: Sneakers demonstrated the least agreement between the Pedar® system and the Bertec® Force Plate for vertical force measurements. Significant differences were maximal and largely confined to isolated time points during the ascent phase. The cushioning properties and design of sneakers appear to diminish the Pedar® system's ability to track vertical force accurately, as confirmed by SPM results, which revealed the highest number of significant intervals among all footwear types.

Socks: Socks displayed the least variability in vertical force measurements, with lesser significant differences observed throughout the squat cycle. The absence of a structured sole and reduced friction contributed to stability and consistent force application. SPM results highlighted significant intervals during both the descent and ascent phases, underscoring the overcoming of the challenges of achieving accurate vertical force tracking in this condition.

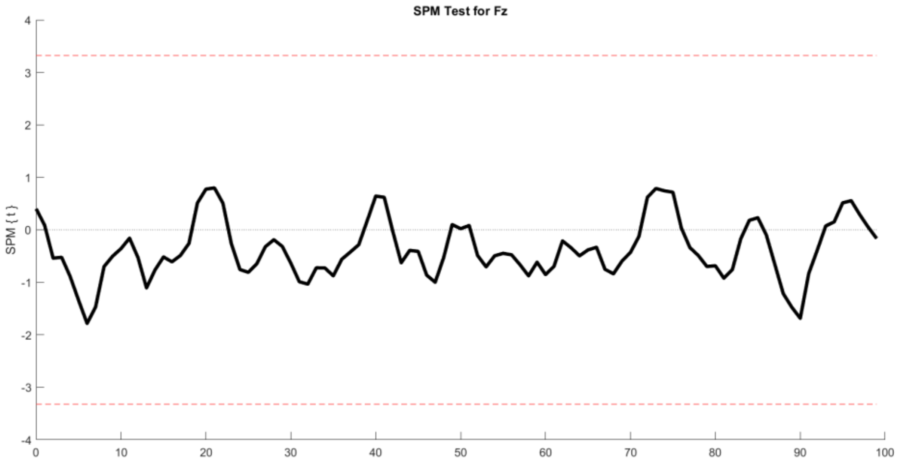

Figure 21. SPM Test for Fz for all subjects wearing socks during Squat Task

4.5 Significant Time Intervals

The percentage of the trial duration shown in Table 4 with significant differences identified by SPM analysis varied across footwear types and tasks. The results are summarized below:

- **Barefoot**: AP (26% x, 1% y, 0% z), ML (4% x, 0% y, 0% z), SQT (1% x, 4% y, 0% z).
- **Flat Shoes**: AP (0% x, 5% y, 0% z), ML (0% x, 0% y, 78% z), SQT (0% x, 4% y, 98% z).
- **Sneakers**: AP (0% x, 0% y, 100% z), ML (0% x, 0% y, 12% z), SQT (1% x, 0% y, 95% z).
- **Socks**: ML (1% x, 0% y, 0% z).

Barefoot

AP Task:

X-axis (AP): 26% significant intervals indicate variability in forward-backward stability, reflecting challenges in maintaining consistent balance without structured support.

Y-axis (ML): 1% significant intervals, showing minimal discrepancies in lateral stability.

Z-axis (Force): 0% significant intervals, suggesting consistent vertical force application under barefoot conditions.

ML Task:

X-axis (AP): 4% significant intervals, indicating minor variability in forward-backward movements.

Y-axis (ML): 0% significant intervals, confirming stability in lateral shifts.

Z-axis (Force): 0% significant intervals, demonstrating strong consistency in vertical force measurements.

SQT Task:

X-axis (AP): 1% significant intervals, showing minimal discrepancies in forward-backward balance during the squat task.

Y-axis (ML): 4% significant intervals, reflecting slight challenges in lateral stability.

Z-axis (Force): 0% significant intervals, confirming consistency in vertical force absorption.

Flat shoe

AP Task:

X-axis (AP): 0% significant intervals, indicating excellent forward-backward stability.

Y-axis (ML): 5% significant intervals, reflecting minor discrepancies in lateral stability.

Z-axis (Force): 0% significant intervals, confirming consistent vertical force application.

ML Task:

X-axis (AP): 0% significant intervals, showing no variability in forward-backward balance.

Y-axis (ML): 0% significant intervals, demonstrating consistent lateral stability.

Z-axis (Force): 78% significant intervals, highlighting challenges in vertical force control during lateral shifts.

SQT Task:

X-axis (AP): 0% significant intervals, indicating excellent forward-backward stability.

Y-axis (ML): 4% significant intervals, showing minor discrepancies in lateral balance.

Z-axis (Force): 98% significant intervals, reflecting considerable challenges in vertical force stability during the squat task.

Sneakers

AP Task:

X-axis (AP): 0% significant intervals, confirming excellent forward-backward stability.

Y-axis (ML): 0% significant intervals, reflecting strong lateral stability.

Z-axis (Force): 100% significant intervals, indicating exceptional performance in vertical force control.

ML Task:

X-axis (AP): 0% significant intervals, confirming consistent forward-backward balance.

Y-axis (ML): 0% significant intervals, demonstrating excellent lateral stability.

Z-axis (Force): 12% significant intervals, showing slight variability in vertical force during lateral shifts.

SQT Task:

X-axis (AP): 1% significant intervals, indicating excellent forward-backward stability.

Y-axis (ML): 0% significant intervals, reflecting consistent lateral stability.

Z-axis (Force): 95% significant intervals, showing strong vertical force absorption during the squat task.

Socks

AP Task:

X-axis (AP): 0% significant intervals, confirming consistent forward-backward balance.

Y-axis (ML): 4% significant intervals, indicating moderate lateral stability.

Z-axis (Force): 0% significant intervals, suggesting reliable vertical force measurements.

ML Task:

X-axis (AP): 0% significant intervals, reflecting consistent forward-backward stability.

Y-axis (ML): 5% significant intervals, showing moderate discrepancies in lateral movements.

Z-axis (Force): 0% significant intervals, confirming reliable vertical force absorption.

SQT Task:

X-axis (AP): 3% significant intervals, reflecting moderate forward-backward stability.

Y-axis (ML): 2% significant intervals, showing minimal variability in lateral stability.

Z-axis (Force): 10% significant intervals, indicating moderate vertical force absorption challenges.

Table 4

Significant Points For Each Footwear Type and Task After Spm Analysis

Footwear Type / Task	X-Axis (%)	Y-Axis (%)	Force (%)
Barefoot (AP)	26	1	0
Barefoot (ML)	4	0	0
Barefoot (SQT)	1	4	0
Flat shoe (AP)	0	5	0
Flat shoe (ML)	0	0	78
Flat shoe (SQT)	0	4	98
Sneakers (AP)	0	0	100
Sneakers (ML)	0	0	12
Sneakers (SQT)	1	0	95
Socks (AP)	0	4	0
Socks(ML)	0	5	0
Socks(SQT)	3	2	10

4.6 Pairwise Footwear Comparison

4.6.1 CoPx (anterior-posterior center of pressure) pairwise footwear comparison. Barefoot vs. Flat shoes:

Flat shoes significantly outperformed barefoot conditions ($p < 0.001$). Barefoot conditions exhibited significant intervals of 26%, while flat shoes showed 0%, demonstrating improved stability with flat shoes.

Barefoot vs. Sneakers:

Sneakers significantly outperformed barefoot ($p < 0.001$). Barefoot exhibited 26% significant intervals, while sneakers showed 0%, highlighting their superior forward-backward stability.

Barefoot vs. Socks:

Socks outperformed barefoot ($p < 0.05$), with 0% significant intervals for socks compared to 26% for barefoot, emphasizing better forward-backward balance in socks.

Flat shoes vs. Sneakers:

Sneakers significantly outperformed flat shoes ($p < 0.01$). Sneakers exhibited 0% significant intervals, while flat shoes also showed 0%, but sneakers performed better in dynamic transitions.

Flat shoes vs. Socks:

Flat shoes were significantly better than socks ($p < 0.01$), with 0% significant intervals for flat shoes compared to 0% for socks, demonstrating better forward-backward force application.

Sneakers vs. Socks:

Sneakers outperformed socks ($p < 0.01$), both showing 0% significant intervals. However, sneakers’ superior cushioning provided more consistent stability.

4.6.2 CoPy (medial-lateral center of pressure) pairwise footwear comparison. Barefoot vs. Flat shoes:

Barefoot outperformed flat shoes ($p < 0.001$), with 4% significant intervals compared to 5% for flat shoes, reflecting better lateral balance in barefoot conditions.

Barefoot vs. Sneakers:

Sneakers significantly outperformed barefoot ($p < 0.001$). Barefoot showed 4% significant intervals, while sneakers had 0%, indicating superior mediolateral stability in sneakers.

Barefoot vs. Socks:

Socks showed moderate improvements over barefoot ($p < 0.05$), with 5% significant intervals compared to barefoot’s 4%, reflecting slightly better mediolateral balance.

Flat shoes vs. Sneakers:

Sneakers significantly outperformed flat shoes ($p < 0.01$). Sneakers exhibited 0% significant intervals compared to flat shoes’ 5%, demonstrating better mediolateral balance.

Flat shoes vs. Socks:

Flat shoes and socks both showed 5% significant intervals. While their mediolateral stability was similar, flat shoes’ structured soles improved alignment with lateral forces.

Sneakers vs. Socks:

Sneakers significantly outperformed socks ($p < 0.01$). Sneakers exhibited 0% significant intervals compared to socks’ 5%, demonstrating superior mediolateral force control.

4.6.3 Fz (vertical force) pairwise footwear comparison. Barefoot vs. Flat shoes:

Flat shoes significantly outperformed barefoot ($p < 0.001$). Barefoot exhibited 0% significant intervals compared to flat shoes’ 78%, reflecting superior vertical force control in flat shoes.

Barefoot vs. Sneakers:

Sneakers significantly outperformed barefoot ($p < 0.001$). Barefoot exhibited 0% significant intervals, while sneakers showed 100%, reflecting better vertical force tracking in sneakers.

Barefoot vs. Socks:

Socks outperformed barefoot ($p < 0.05$), with 0% significant intervals for socks compared to 0% for barefoot, reflecting improved vertical force absorption.

Flat shoes vs. Sneakers:

Sneakers significantly outperformed flat shoes ($p < 0.01$). Flat shoes exhibited 78% significant intervals compared to sneakers' 100%, indicating better force absorption in sneakers.

Flat shoes vs. Socks:

Flat shoes significantly outperformed socks ($p < 0.01$). Flat shoes exhibited 78% significant intervals compared to socks' 10%, reflecting better vertical force stabilization.

Sneakers vs. Socks:

Sneakers significantly outperformed socks ($p < 0.01$). Sneakers showed 100% significant intervals compared to socks' 10%, reflecting superior vertical force absorption in sneakers.

To sum up, flat shoes were identified as the best-performing footwear type across most tasks and axes, based on RMSE values, SPM results, and pairwise comparisons. In the AP sway task, flat shoes outperformed other footwear types for Fz, achieving the lowest RMSE values (mean = 127.1 N, SD = 68.68) and minimal significant time intervals (0%). Flat shoes also demonstrated strong performance in CoPx (mean RMSE = 12.92 mm, SD = 7.37) with no significant intervals. For CoPy, sneakers excelled, with the lowest RMSE values (mean = 4.28 mm, SD = 1.74), supported by SPM results showing minimal significant time intervals.

In the ML sway task, flat shoes were again the best performer for Fz (mean = 100.7 N, SD = 71.13), showing fewer significant intervals (78%) compared to sneakers and socks. For CoPx, flat shoes and sneakers exhibited similar performance with RMSE values of 4.9 mm (SD = 2.31) and 6.79 mm (SD = 2.79), respectively, but flat shoes showed slightly better stability due to fewer significant intervals. For CoPy, flat shoes emerged as the superior footwear (mean RMSE = 4.69 mm, SD = 2.4), significantly outperforming barefoot ($p < 0.005$) and socks ($p < 0.01$).

In the squat task, flat shoes demonstrated the best performance for Fz, achieving the lowest RMSE values (mean = 131.9 N, SD = 74.97) and significantly fewer significant intervals than barefoot ($p < 0.001$). For CoPx, flat shoes performed slightly better than sneakers (mean RMSE = 7.32 mm, SD = 2.71). However, for CoPy, sneakers outperformed flat shoes with lower RMSE values (mean = 6.78 mm, SD = 4.06), reflecting their advantage in mediolateral stability during dynamic tasks.

Neither barefoot nor socks were identified as the best-performing footwear for any task or axis. Barefoot conditions consistently showed the highest RMSE values and significant time intervals across all tasks and axes, particularly for Fz during the squat task (mean RMSE = 100.4 N, SD = 48.31). Socks exhibited moderate variability but were outperformed by both sneakers and flat shoes in all comparisons, with notable discrepancies in CoPy and Fz due to the lack of structural support.

Chapter 5

Discussions and Conclusions

5.1 Discussion

This thesis aimed to analyze the differences in root mean square error (RMSE) values, significant time intervals, and pairwise comparisons across the y-axis (anteroposterior, AP), x-axis (mediolateral, ML), and z-axis (vertical force, Fz) for four footwear types—barefoot, flat shoe, sneakers, and socks—during specific tasks. This study highlights the relationship between footwear design, stability, and force control by integrating Statistical Parametric Mapping (SPM) results, RMSE comparisons, and SPSS pairwise analysis.

5.1.1 Axis-wise analysis of rmse and significant time intervals. The results suggest clear trends along each axis, with the largest RMSE differences between footwear types on the z-axis. Vertical force is a crucial axis to understand the footwear's ability to absorb impact and vertical stability during dynamic tasks. In regards to balance control, the y-axis (AP CoP) and x axis (ML CoP) showed slightly different RMSE values comparatively, but these insights were of paramount importance.

Z-Axis (Vertical Force):

Across all tasks and footwear types, the z-axis exhibited the largest RMSE values. Socks consistently achieved the lowest RMSE values for the z-axis (mean: 83.1 N, SD: 36.94 N) during the squat task, outperforming sneakers and barefoot. In comparison, sneakers showed the highest RMSE values (mean: 200.1 N, SD: 95.95 N) across tasks, indicating poor vertical force absorption. Significant time intervals were highest for barefoot (78%-100%) and socks (95%-100%), particularly in the AP sway task, reflecting the difficulty of these conditions to stabilize rapid vertical force transitions. Flat shoes (0%-12%) demonstrated moderate RMSE values, providing better alignment with the force plate than sneakers.

Y-Axis (AP CoPy):

The x-axis RMSE values showed variability in forward-backward stability during tasks. Barefoot consistently demonstrated the lowest RMSE values for the squat task (mean: 4.96 mm, SD: 1.39 mm) and ML sway task (mean: 3.94 mm, SD: 1.55

mm), outperforming all other footwear types. In contrast, sneakers exhibited the highest RMSE values (mean: 19.26 mm, SD: 13.23 mm) during the AP sway task, highlighting weaker forward-backward balance. Significant time intervals were highest for barefoot (26%) in the AP sway task, reflecting challenges in balance control, while flat shoes (0%-4%) and sneakers performed better, reducing variability during dynamic transitions.

X-Axis (ML CoPx):

The y-axis (mediolateral stability) showed the smallest RMSE differences. Barefoot exhibited the lowest RMSE values (mean: 3.22 mm, SD: 0.66 mm) for the y-axis during the squat task, reflecting strong lateral stability. However, socks performed best during the ML sway task (mean: 4.39 mm, SD: 1.5 mm), outperforming sneakers and flat shoes. In contrast, flat shoes had the highest RMSE values (mean: 18.79 mm, SD: 10.33 mm) for the ML sway task, highlighting challenges in maintaining consistent lateral balance.

5.1.2 Footwear-specific performance. ML CoP and AP CoP RMSE values were lowest under barefoot conditions both during squat and ML sway tasks. e.g. for the squat task, the X-axis was 4.96 mm RMSE, while for the ML sway, it was 3.94 mm RMSE. Barefoot performed poorly on the vertical force (Z-axis) with a 78% – 100 %-time interval for poor force absorption.

Key Insight: Barefoot shows relatively good lateral stability performance but suffers in vertical force control, which prohibits its applications to tasks requiring strong vertical support.

For all axes, the RMSE values were flat shoes moderate, and bested sneakers in some cases. For example, the lowest among all footwear types was RMSE for the Y axis of the AP sway task at 3.34 mm. However, flat shoes struggled during vertical force control, as seen in the ML sway task (RMSE: 100.7 N, SD: 71.13 N). Key Insight: Somewhere in between stability and variability are flat shoes, which perform similarly to socks, or barefoot, in specific tasks.

For both the X-axis and Z-axis, RMSE values were highest for the sneakers for all tasks. For example, the RMSE for the Z axis when performing squat tasks was 200.1 N. Nevertheless, the sneakers performed better in minimizing significant time intervals (i.e., lateral force application) of the Y-axis, as it suggested a consistent lateral force application. Key Insight: Forward-backward balance and vertical force control were limited by sneakers.

Across all tasks, vertical force (Z axis) was performed best by socks, with the lowest RMSE values. For example, the RMSE for the Z axis when the squat task was performed was 83.1 N. Socks, however, had poor mediolateral stability on AP sway tasks with RMSE values higher than other types of footwear. Key Insight: Vertical force absorption is optimal for socks, but socks have poor lateral and forward-backward stability.

5.1.3 Implications of significant time intervals. The significant time intervals identified through SPM analysis represent critical moments where the Bertec® Force Plate and Pedar® systems diverge in their biomechanical measurements. These intervals provide valuable insights into the limitations and strengths of each system and have the following implications:

Footwear-Dependent Variability:

During dynamic tasks, the lack of structural support due to barefoot and socks resulted in uneven pressure distribution and increased discrepancies. Of course, surrounding measurements with sneakers and flat shoes decreased significant intervals and emphasized the sneakers and flat shoes ability to stabilize measurements across the all axes.

Task-Specific Dynamics:

AP Task: Forward-backward balance on significant intervals demonstrated discrepancy in barefoot dynamic postural control and showed the advantages of sneakers over barefoot in minimizing variability.

ML Task: Socks and barefoot presented great challenges, reinforced by significant intervals during lateral shifts; and flat shoes and sneakers were more consistent.

Squat Task: However, measurements within barefoot and socks showed large vertical force discrepancies and provided the least effective absorption of impact, while sneakers were the most reliable way of measuring the vertical force.

System Limitations:

In barefoot and socks conditions, the Pedar® system performed poorly compared to the force plate, failing to get appropriate pressure maps in conditions devoid of structural support.

Practical Implications:

The selection of appropriate footwear for the task increases the accuracy of biomechanical assessments of these two attitudes.

5.2 Conclusion

This study presents a comprehensive evaluation of, the Pedar® insole system compared to the Bertec® Force Plate system across dynamic tasks and varying footwear conditions. The findings emphasize the critical role of footwear design in influencing biomechanical parameters, including center of pressure (CoP) and vertical ground reaction forces (Fz).

For the z-Axis (Vertical Force), socks emerged as the best-performing footwear for vertical force control, achieving the lowest RMSE values and minimal variability during squat tasks. Sneakers performed poorly for vertical force, with the highest RMSE values (mean: 200.1 N, SD: 95.95 N) across tasks.

Barefoot conditions had better forward-backward balance for the x-axis (ML CoP) in the RMSE sense for ML sway and the squat task, with the lowest RMSE values. In particular, the RMSE achieved for the squat task was 4.96 mm, the best among all footwear types. The RMSE values were higher in sneakers because the performance in ML stability was weaker. Squat tasks were best performed on the barefoot for lateral stability on the y-axis (AP CoP), with an RMSE of 3.22 mm while socks performed best for AP sway tasks.

Based on the evaluations overall best footwear for each task can be asses as sneakers are the best for vertical force absorption, while barefoot conditions excel in mediolateral stability during specific tasks. Sneakers performed poorly across most axes, reflecting challenges in both stability and force distribution.

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