

## Gait Analysis for Walking on Flat Footwear and High Heels

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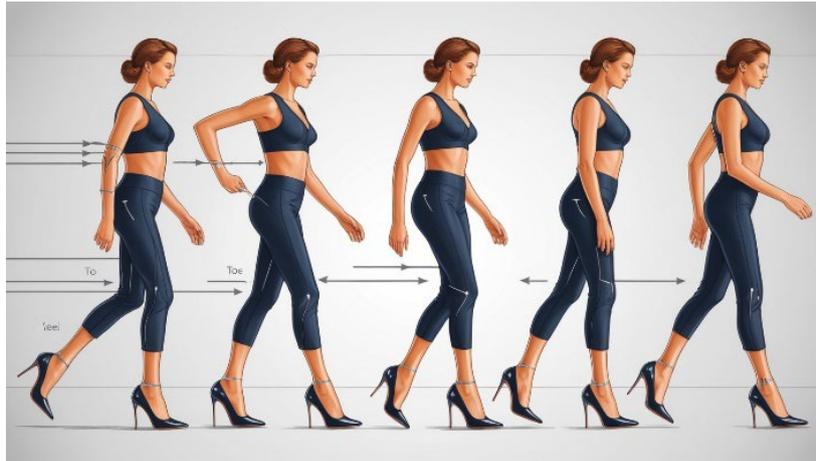
### Abstract

Gait analysis has transformed traditional methods of studying human locomotion by enabling precise monitoring and real-time analysis of critical biomechanical parameters. The purpose of this project is to design a portable gait analysis system as a prototype to evaluate the effects of different footwear on walking dynamics. The acceleration sensor was implemented into a wearable device to collect data and analyze gait variations between walking in flat footwear and high heels. The system monitors angular velocity, acceleration, and angles across three axes (x, y and z). Key features of this system include its ability to record motion data in real time using the WitMotion mobile application. The application visualizes gait parameters, enabling users to identify and understand how different footwear impacts balance, posture, and muscle activation. This portable and user-friendly device offers an accessible alternative to traditional gait analysis tools, making it suitable for individuals, clinicians, and researchers. The resulting system is a practical solution and a cost-effective innovation that bridges the gap between advanced gait analysis and real-world applications.

## 1. Introduction

The simplest and most common way of performing exercise is "Walking", human locomotion is not just an activity but specifies numerous details within it included maintaining balance and controlling the movement [1]. In a typical gait cycle, each leg alternates between two main phases: the stance phase, where the foot is in contact with the ground, and the swing phase, where the leg swings forward to prepare for the next step. Efficient walking requires a smooth, rhythmic motion with balanced weight distribution and coordinated muscle activity.

Fig. 1 highlights the key phases of a walking stride, focusing on posture, leg alignment, and proper foot placement when walking by wearing high heels. The model in the figure starts walking by leading with her heels touching the ground first. Her arms swing naturally, with the opposite arm moving forward as the leg steps. As the step progresses, the weight shifts onto the flat foot, providing balance. The opposite leg begins to lift, preparing for the next step. Next, the foot rolls forward, transferring weight to the toe area, which becomes the last point of contact as she pushes off. This phase engages the calf muscles. With the toe pushing off, the opposite leg swings forward, while the arms continue their natural swinging motion for balance. Lastly, the back leg fully lifts off the ground, and the front wheels prepare to strike again, completing the stride cycle.



**Fig. 1** Gait phase when wearing high heels. This figure is produced using Leonardo.ai

Walking in high heels causes a significant change in how people move, often impacting stability, balance, and joint alignment. These changes may not have an obvious impact on humans in the short term but can contribute to discomfort and long-term issues. For example, wearing high heels can lead to muscle fatigue and joint strain due to the unnatural posture and weight distribution since the muscle keeps contracted by elevate heel position more shortens. Fig. 2 emphasize the difference of body posture, stride, and muscle activation between flat shoes walking and walking by wearing high heels. It can be concluded that normal walking in sports shoes promotes better posture, balance, and muscle function compared to high heels walking, which places additional strain on the body due to the unnatural foot position and altered center of gravity.



**Fig. 2** The difference between high heels walking and normal walking. This figure is produced using Leonardo.ai

Table 1 indicates the difference between 2 types of walking in a few characteristics. The body posture of high heels walking is body will shift forward which cause the back arches slightly to maintain balance, which places additional strain on the lower back while normal walking performed upright posture with a neutral spine position. The stride length indicated the distance covered between two successive placements of the same foot during walking. Besides, Stride length of normal walking is longer than high heels walking. It is presented that the step length of high heels walking is shorter than that of both flat-heel and sneaker walking [2]. High heels walking causes the foot downward while normal walking can perform healthy heel-to-toe pat-tern. Lastly, wearing high heels will increase activation in the muscle such as calves and quadriceps to maintain stability. However, the calf, hamstring, and glute muscles work in harmony, with less strain on the lower leg muscles compared to high heels

walking in normal walking. In a summary, when walking wearing high heels shoes, the leg muscles are doing a greater job than a normal gait [3].

**Table 1** Comparison between high heels walking and normal walking

Characteristics	High Heels Walking	Normal Walking
Posture	Body to shift forward	Upright posture with a neutral spine position
Stride Length	Shorter	Longer
Foot Position	Foot in downward	Heel-to-toe pattern
Muscle Activation	Increased activation in the calves and quadriceps to maintain stability	Balanced muscle engagement

Currently, gait analysis systems capable of examining such changes are costly and require complex setups, which limits their availability for everyday users or clinics with tighter budgets. Gait analysis continues to be an important technique for many clinical applications to diagnose and monitor certain diseases [4]. Consequently, there is a growing demand for a practical and accessible alternative that can deliver insights into walking patterns without the high cost or specialized equipment [5].

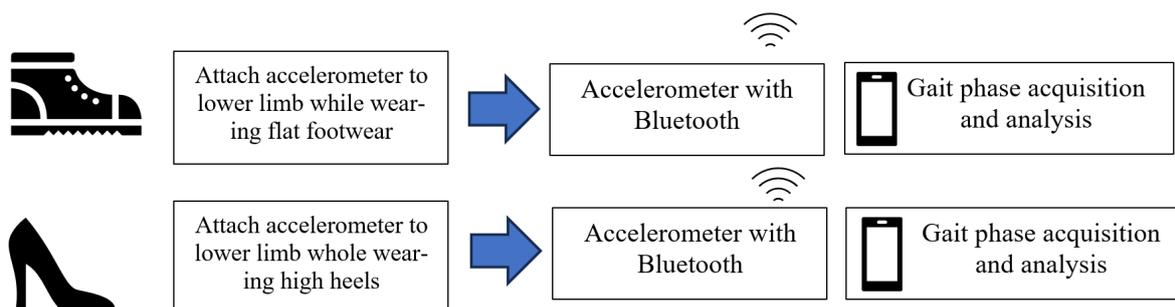
In this project, an affordable, portable gait analysis device using an accelerometer will be developed to monitor gait analysis when flat shoes walking and walking while wearing high heels. Unlike traditional methods, this compact and wearable device will allow for real-time gait monitoring, focusing on detecting variations between walking in high heels and regular flat footwear. By capturing metrics such as step length, rhythm, and balance indicators, the device will offer valuable data on how high heels can change the walking dynamics. This tool will not only serve individuals interested in understanding their walking patterns but also clinicians who may use it as a supportive tool in gait analysis, enabling better guidance on footwear choices or preventive care [5].

## 2. Methodology

In this section, the methodology to complete the project is explained comprehensively by encompassing the block diagram, participant, apparatus and experiment set up. The proposed gait analysis system is implemented in phases to assess walking patterns for individuals wearing flat footwear and high heels walking on flat ground. In the first phase of implementation, an accelerometer sensor was used to measure angular velocity, acceleration, and angles along the x, y, and z axes during gait cycles. The recorded data was analyzed to assess the impact of footwear type on balance, posture, and stability. In the second phase, the system incorporates advanced visualization and monitoring features. Users can observe gait characteristics in real time via an application, ensuring a comprehensive understanding of the gait patterns. The results demonstrated that the system effectively captures gait variations, highlighting distinct differences between walking with flat footwear and high heels.

### 2.1 Block Diagram

Fig. 3 shows the block diagram of the project. 9-axis Bluetooth Gyroscope Accelerometer Sensor (BWT901CL) was used for monitoring and acquiring the gait phases. The accelerometer was the main sensor used to achieve the objectives. The sensors captured the acceleration, angular velocity and angle in 3-axis in x, y and z. The accelerometer transmits the collected data wirelessly via Bluetooth to the mobile application (WitMotion APP). This wireless communication ensures real-time data transfer and enhances the system's portability and user convenience within 7 meters of distance. The system segregates the data based on the type of footwear which is flat shoes and high heels. The results were visualized as graphs to compare the walking performance between flat shoes and high heels.



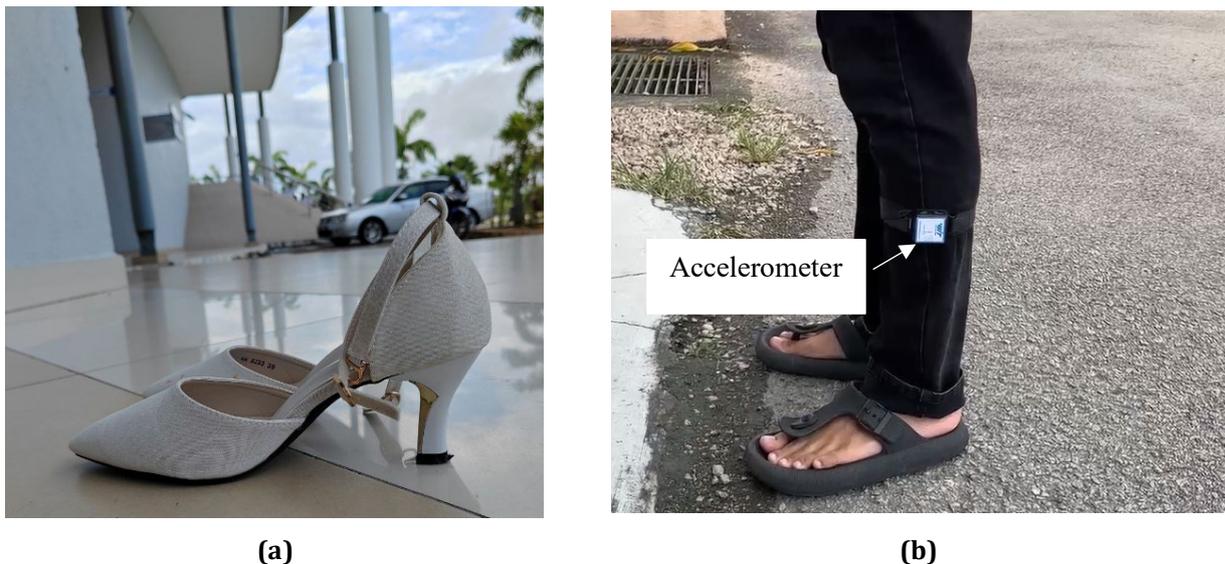
**Fig. 3** Block diagram of the data measurement

## 2.2 Participant

Two healthy participants recruited in the experiment. Participant A is a female at an age of 23 years old with the height of 166 cm, 60Kg while Participant B is a male at the age of 24 years old with height of 164cm, 51Kg. Both individuals were selected based on their overall good health and the absence of any known musculoskeletal or neurological conditions that could impact gait mechanics. This selection aimed to ensure that the data collected represented normal walking patterns without the influence of external factors.

## 2.3 Apparatus and Experiment Set Up

The implemented system was carried out through the experiment to collect data by the healthy object wearing flat shoes and high heels walking on flat ground. The objects were asked to walk on flat ground for 10 steps. Fig.4 (a) shows the high heels with a height of 3 inches worn by the objects during the experiment. The flat ground environment was selected to replicate a real-world scenario, where individuals may encounter flat surfaces during walking activities. To ensure the motion data was captured accurately, an accelerometer sensor was securely fastened to the calf as illustrated in Fig. 4(b). This positioning was chosen to optimize the detection of angular velocity, acceleration, and angular velocity during the gait cycle. A phone application, 'WitMotion' was used for real-time monitoring and recording of the measuring parameters.



**Fig. 4** (a) High heels wore for the experiment; (b) Placement of accelerometer

## 3. Result and Discussion

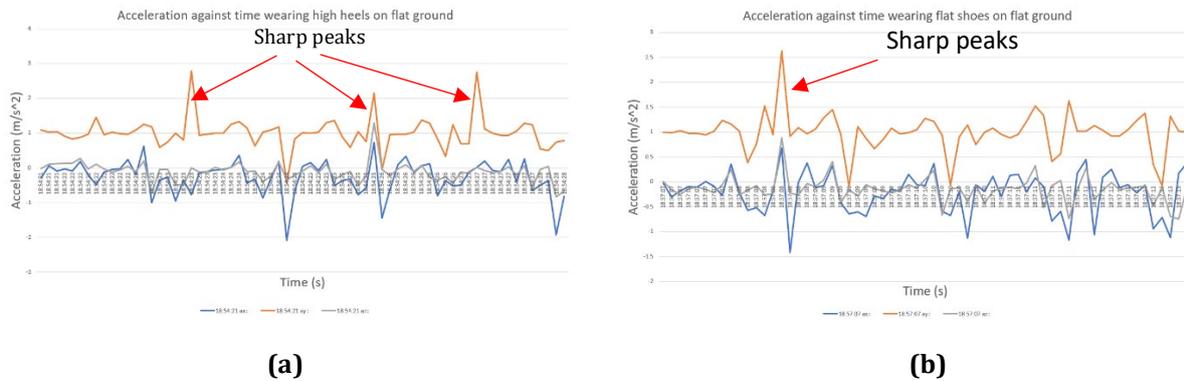
The data collected from the experiment underwent comprehensive analysis to evaluate the impact of different footwear types on gait dynamics in x-axis, y-axis, and z-axis. According to Anita Sant'Anna et al., 2009 [6], the x represents the vertical axis, y is horizontal axis which perpendicular to the walking direction and z is the horizontal axis in pointing the walking direction. The parameter of measurement are acceleration ( $m/s^2$ ), angular velocity (deg/s) and angle (degree). Acceleration measured the of changes in velocity during movement and the gravitational acceleration caused by the microstructures being displaced with the gravitational field [4]. The angular velocity defined the rate of change of angular displacement with respect to time while the angle corresponding to orientation or position of a body segment relative to a reference frame. The data was analyzed based on the comparison of object wearing flat shoes and high heels walking on flat ground for each participant individually. The findings underscore the significant biomechanical impact of high heels walking, compared to the natural and balanced movement associated with flat shoes.

### 3.1 Comparison of Acceleration on Flat Ground between Flat Shoes and High Heels of Participant A

Fig. 5(a) and Fig. 5(b) highlighted clear differences between walking in wearing high heels and flat shoes. When walking in high heels, the acceleration patterns, particularly along the Y-axis (orange line), display sharp peaks and significant variations, suggesting increased instability and greater force exertion to maintain balance [7]. The positive spike indicates an increase in speed and negative spike indicate the deceleration of movement.

Additionally, the X-axis (blue line) and Z-axis (gray line) show frequent spikes, indicating uneven forward motion and additional adjustments due to the shifted posture caused by high heels. A previous work indicates that altered gait patterns from high heels may cause excessive vertical force and misalign the body's natural center of gravity, leading to instability and discomfort [8].

However, flat shoes walking reveals smoother and more consistent acceleration patterns across all axes. Instead of the sharp spikes seen in high-heel walking, the Y-axis shows smaller and more regular variations, reflecting a steady and controlled gait. This observation aligns with findings that suggest normal walking minimizes excessive muscular effort, promotes joint stability, and reduces compensatory movements [9]. Similarly, the X-axis and Z-axis maintain fewer sudden changes, indicating minimal compensatory movements and a more natural transition between steps. This comparison underscores the impact of footwear, where walking in high heels introduces greater instability (higher acceleration) and requires more energy, whereas normal shoes promote balanced and efficient movement.

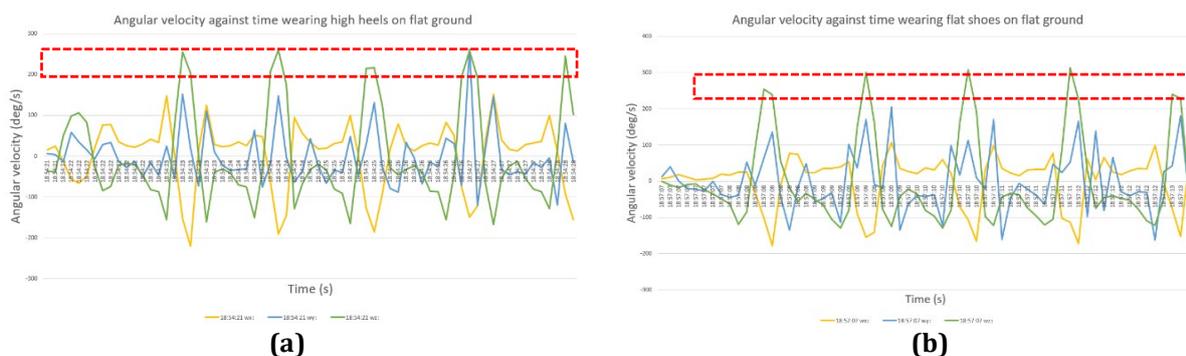


**Fig. 5** (a) Acceleration when wearing high heels; (b) Acceleration when wearing flat shoes

### 3.2 Comparison of Angular Velocity on Flat Ground between Flat Shoes and High Heels Participant A

Fig. 6(a) and (b) show that the angular velocity of the z-axis in flat shoe walking (>300) is higher than high heels walking (<300). The higher angular velocity indicated the larger rotational movements. Benjamin F. Mentiplay et al., 2018 [10] found that the angular velocity increased when the stride rate increased [10]. As the stride rate increases, there is a corresponding rise in the angular velocity of the lower limb segments to accommodate the faster cyclic motion required for quicker strides. Besides, the performance of angular velocity of high heels walking is more irregular compared to flat shoes walking. Hence, the stride length and stride rate of high heels walking are more unbalanced.

Maintaining a balance between stride length and stride rate is crucial for optimal gait performance. Overstriding (excessively increasing stride length) can disrupt the natural gait cycle, leading to increased ground reaction forces and joint stress. This imbalance can result in inefficient motion patterns and elevate the risk of injury [11]. In other words, this balance not only improves performance during walking but also plays a critical role in preventing injuries.



**Fig. 6** (a) Angular when wearing high heels; (b) Angular velocity when wearing flat shoes

### 3.3 Comparison of Angle on Flat Ground between Flat Shoes and High Heels Participant A

In high-heel walking, Fig. 7(a), the angles, particularly Angle Y (orange line) and Angle Z (gray line), show larger fluctuations, indicating reduced stability and more uneven movements. Cowley et al., 2009 [7], concluded high-heels footwear alters posture and gait mechanics, increasing instability and requiring compensatory movements to maintain balance. Angle Y exhibits significant swings, suggesting greater stress and movement due to the shifted weight and altered posture caused by high heels. This aligns with findings from Cho et al., 2004 [12], who observed that females walking in high heels experience higher stress on the lower extremities due to changes in leg alignment and center of gravity [12]. Angle Z also shows noticeable variations, reflecting compensatory adjustments to maintain balance, which is further supported by [13], who found that females exhibit greater ankle motion when wearing high heels compared to flat shoes walking.

In contrast, flat shoes walking displays smoother and more consistent patterns across all angles, with Angle Y showing regular but less extreme variations and Angle Z remaining relatively flat as illustrated in Fig. 7(b). This indicates that walking in normal shoes requires fewer adjustments, resulting in better balance and stability. Cowley et al., 2009 [7], emphasized that flat or low-heeled shoes promote a more natural gait cycle, ensuring even weight distribution and reducing unnecessary strain on joints.

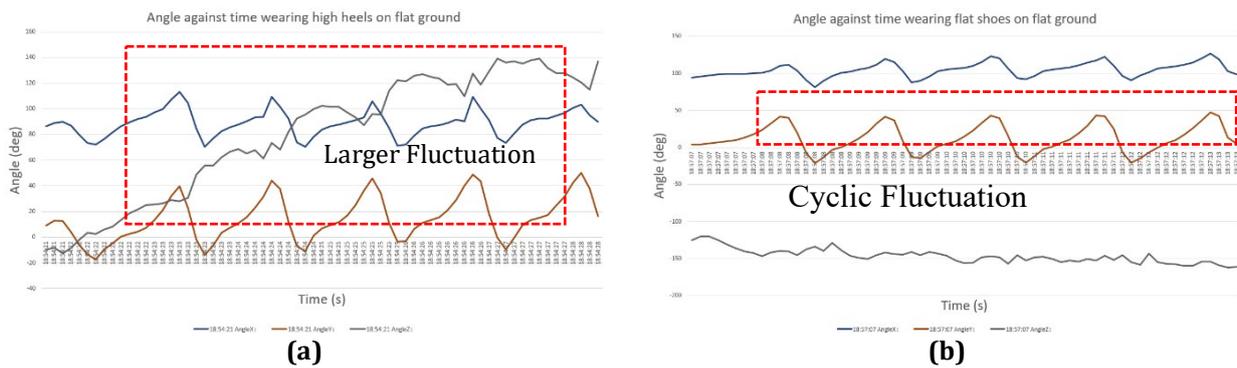


Fig. 7 (a) Angle when wearing high heels; (b) Angle when wearing flat shoes

### 3.4 Comparison of Acceleration on Flat Ground between Flat Shoes and High Heels of Participant B

The comparison of acceleration over time for flat shoes walking versus high heels on flat surfaces shows clear differences in stability and movement patterns. For flat shoes walking, 8(b), the y-axis acceleration generally stays around 1, with occasional peaks reaching up to 2.5. The sharp early peak in the y-axis for flat shoes might be due to human errors during data collection, such as an awkward first step, uneven footing, or a sudden change in walking pace at the start. In contrast, walking in high heels, Fig. 8(a), shows a much wider range of y-axis acceleration, with peaks reaching as high as 3 and more dramatic dips. This suggests that walking in high heels is less stable and requires more effort to maintain balance.

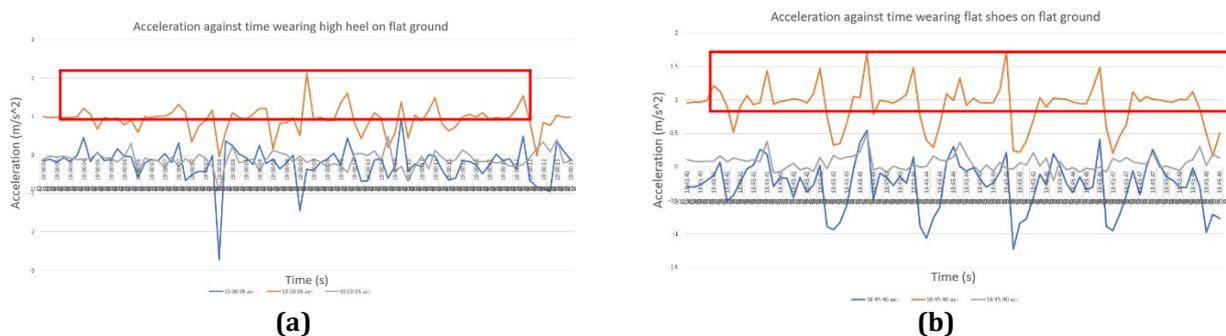


Fig. 8 (a) Acceleration when wearing high heels; (b) Acceleration when wearing flat shoes

Both graphs display periodic peaks and dips that correspond to the natural rhythm of walking, but the peaks in the high heels graph are much more pronounced, especially in the y-axis. This highlights the extra strain and adjustments needed when walking in high heels. Overall, flat shoes walking appears to be steadier and more

stable, while high heels introduce more fluctuations and instability, requiring greater effort to maintain balance. Meanwhile, the high heels graph reveals greater variability in these axes, indicating lateral instability and the challenges of walking in high heels.

### 3.5 Comparison of Angular Velocity on Flat Ground between Flat Shoes and High Heels of Participant B

When comparing the data, walking in high heels shows more instability than flat shoes walking. The z-axis (up and down rotation) has bigger and more uneven peaks, close to 300, which means the legs are moving more irregularly as showed in Fig. 9(a). The y-axis (side-to-side motion) also has more changes, showing that it's harder to stay balanced in high heels. This happens because high heels change how the foot hits the ground, making it tougher to walk naturally and smoothly.

On the other hand, wearing flat shoes has smaller, smoother, and more even peaks, especially in the z-axis as illustrated in Fig.9(b). This shows a steady and natural movement where the steps are consistent and balanced. There's also less side-to-side motion, meaning it's easier to stay stable. Overall, walking in high heels disrupts the natural walking pattern, while flat shoes walking keeps the motion smooth and balanced. This is supported by research showing that high heels increase postural sway and reduce walking stability due to altered foot mechanics [14].

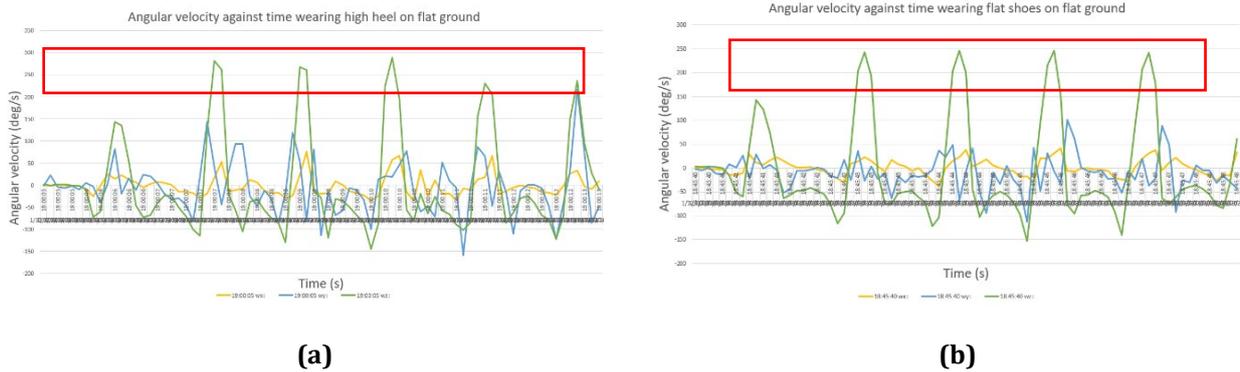


Fig. 9 (a) Angular velocity when wearing high heels; (b) Angular velocity when wearing flat shoes

### 3.6 Comparison of Angle on Flat Ground between Flat Shoes and High Heels of Participant B

High heels walking exhibits constrained and more controlled motion as showed in Fig. 10(a). The orange line (Angle Y) shows smaller, dampened oscillations compared to walking by wearing flat shoes which indicate restricted stride motion due to the footwear. A significant feature is the sharp spike in the grey line (Az), marked as "Moment of Instability", which represents a sudden, significant change in vertical motion. This spike likely results from difficulty maintaining balance or a disruption in walking rhythm because high heel forces the foot into plantar flexion [3], which is not observed in normal walking. Additionally, the blue line (Angle X) remains steady with minimal variation, reflecting reduced lateral motion during high-heels walking.

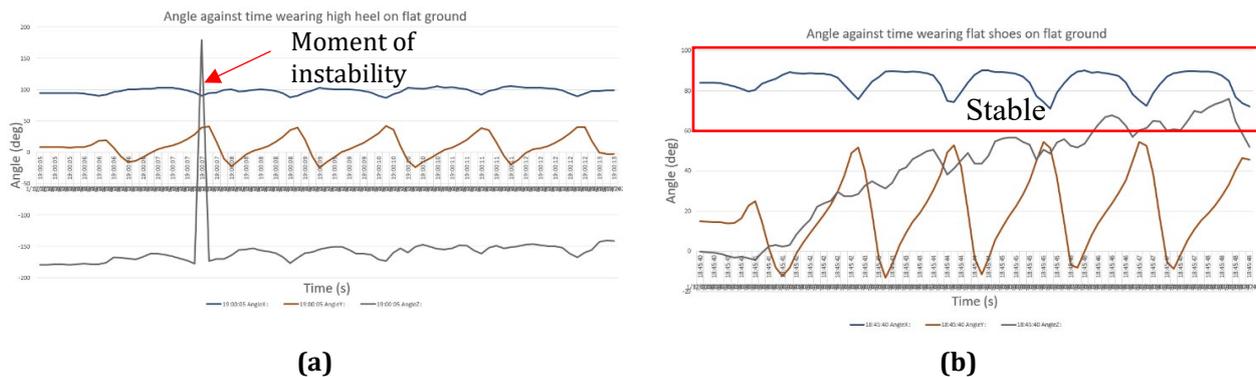


Fig. 10 (a) Angle when wearing high heels; (b) Angle when wearing flat shoes

During flat shoes walking in Fig. 10(b), the Angle X showed stable performance compared to Angle Y and Angle Z. Angle X appears to fluctuate minimally with consistent peaks and troughs, suggesting stable changes in angle over time. However, the Angle Y demonstrated an increased waveform along the walking period which indicating progressive variability or shifts in lateral motion throughout the walking period.

#### 4. Conclusion

In conclusion, high-heel walking places greater demands on muscles and joints, as the body must constantly adjust to maintain posture and balance. High heels shift the body's weight forward, leading to exaggerated movements and increased strain, instable acceleration as reflected in the larger angle changes. On the other hand, normal walking distributes weight evenly and follows a natural walking pattern, leading to smoother and more stable movements. These findings highlight how footwear significantly influences walking stability and strain, with high heels introducing greater challenges compared to normal shoes. Normal walking with flat footwear promotes a more stable and efficient gait, with less risk of musculoskeletal discomfort. These findings underscore the importance of considering the biomechanics of footwear in promoting healthy walking patterns and minimizing strain.

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#### Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

#### Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Muhammad Asyraf Danial, Muhammad Asri, Chin Phong Soon; **data curation:** Yek Nai Chuan, Mahdzir Jamiaan; **analysis and interpretation of results:** Soh Jia Yi, Harith Aiman, Yek Nai Chuan; **draft manuscript preparation:** Soh Jia Yi and Chin Phong Soon. All authors reviewed the results and approved the final version of the manuscript.

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