Report for OATech+ Funded Internship with the Institute of Digital Healthcare, WMG, University of Warwick:

Analysing Footfalls & Heartbeats fabric sensor data for gait assessment

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Abbreviations

HC = Heel Contact; TO = Toe-off;

1 Introduction

Osteoarthritis is a degenerative joint disease which commonly occurs in the knee. Knee osteoarthritis can be examined by the standard in-lab gait analysis. However, wearable sensor systems allow for real gait analysis outside the lab. Gait analysis helps to understand the biomechanics in knee osteoarthritis development and to plan therapeutic intervention.

Motion capture systems are considered the gold standard for gait analysis, however they are expensive and can only capture a small number of consecutive steps in a small capture volume. This limits the averaged gait data and is uncertain whether the motion capture data are similar to natural walking patterns.

2 Overview

This report describes the outcomes for the Footfalls & Heartbeats' smart shoes.

A pair of smart shoes was provided with sensors embedded in the soles of the shoes. Each shoe had four sensors; three sensors were positioned at the top toe, ball left side and ball right side of the toe region, and the fourth sensor was placed in the heel of the shoe.

Data from the smart shoes was used to identify heel contact and toe-off during the gait cycle for both the right and left shoes. The gait parameters: stride time, stance time and swing time, were calculated from the data collected. The gait parameters from the smart shoes were then compared to the gait parameters from the motion capture system.

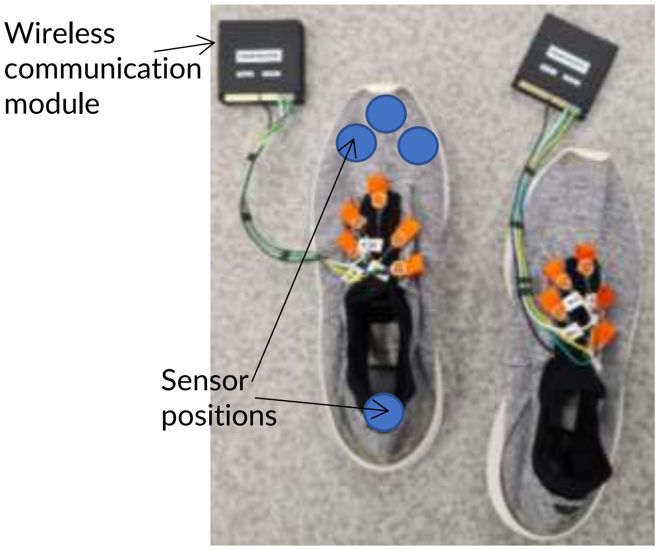

Figure 1: Footfalls & Heartbeats' smart shoes

3 Method

Data from the smart shoes was collected by adding four ground contact forces to each of the four sensors in the left and right shoe. The ground contact force signals are transferred to the host computer via wireless communication.

MATLAB algorithms were used to identify; TO and HC and calculate the gait parameters for both left and right smart shoes.

For verification of the reliability of the smart shoes method, Qualisys Motion Capture System was utilised. The marker-based Motion Capture System consists of eight cameras.

Figure 2: Marker setup for Qualisys Motion Capture System

3.1 Data Pre-processing

Straight walks up and down the lab was conducted for the walking trials.

3.2 Preliminary Data Analysis

For the detection of gait events; HS and TO as the initial and final foot contact during gait, and the estimation of the duration of gait cycles (stride time) and gait phases (stance and swing duration).

Heel contact was identified when the resistance suddenly decreased as pressure was applied to the sensor. The resistance increased as the pressure was reduced on the sensor. Toe-off identified when resistance suddenly increased as no pressure was applied to the sensor when the foot was lifted from the ground.

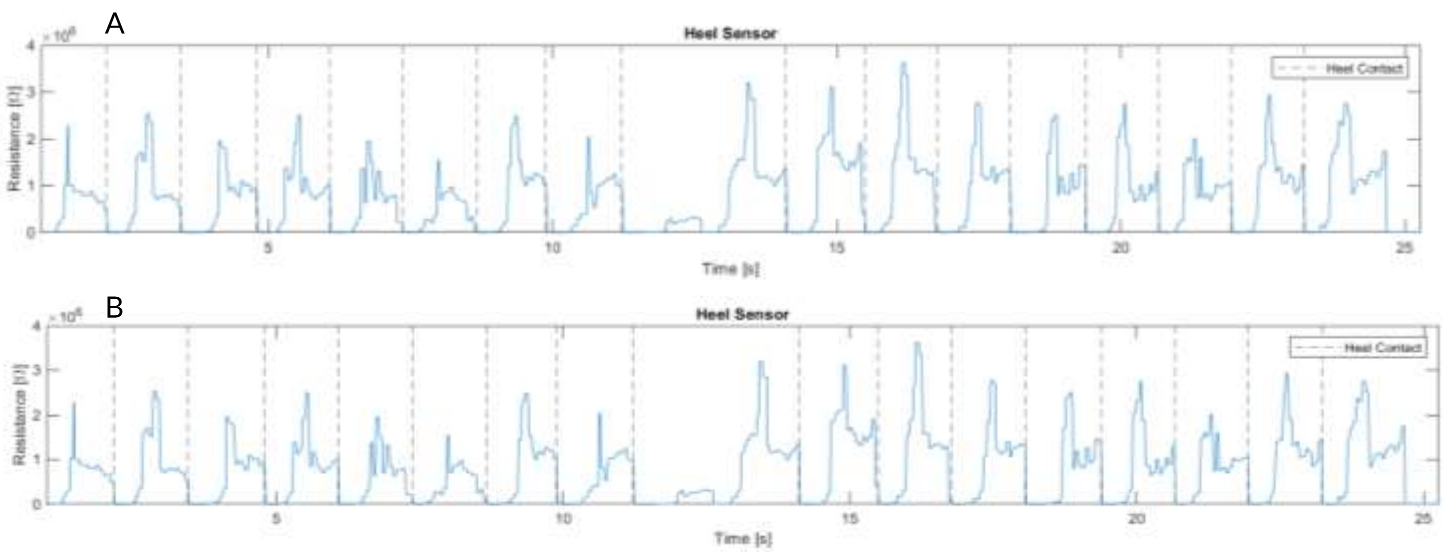

Figure 3: (A)Left shoe (B)Right shoe. Gait phases and resistance of the heel sensor during a walking trial.

3.3 Detecting Heel Contact

Heel contact was identified as the troughs and the sudden increase in resistance values when iterating backward through the samples. The minimum force value on the heel is below a certain threshold when comparing resistance values.

3.4 Detecting Toe-off

An average of the ball right side and ball left side toe sensors was used to calculate toe-off, as the top toe sensor always missed to detect the toe-off. Toe-off was identified as the peaks and the sudden increase in resistance values when iterating forward through the samples. The average of the ball right side and ball left side toe force sensors above a threshold were used to estimate toe-off.

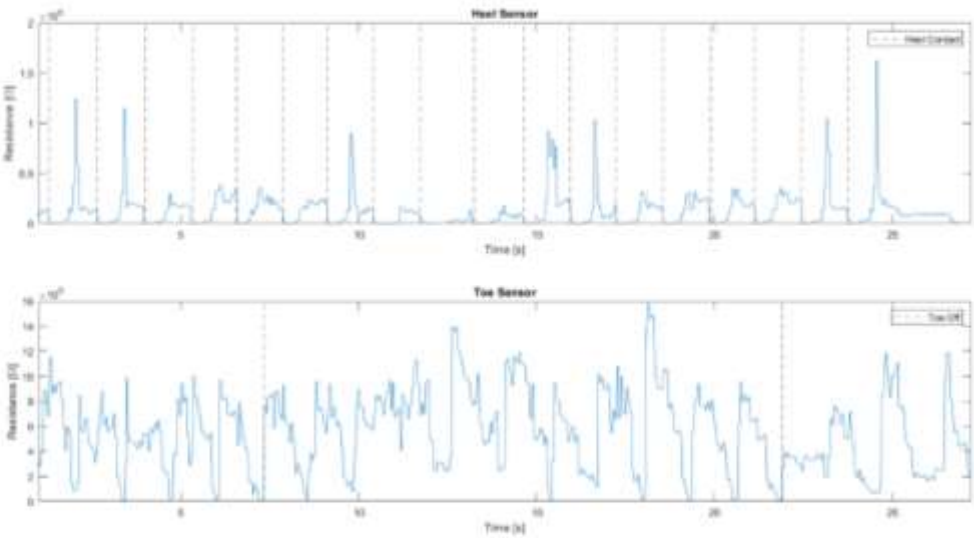

Figure 4: Heel sensor was used to detect heel contact. Top toe sensor could not be used to identify toe-off.

3.5 Gait Parameters

The heel contact and toe-off were used to calculate the gait parameters.

- Stride time: time during one complete gait cycle, from heel contact to heel contact, by the same leg.
- Stance time: time during which the foot is in contact with the ground, from heel contact to toe-off.
- Swing time: time during which the foot is in the air, from toe-off to heel contact.

4 Results

4.1 Gait Parameters

To test the accuracy of the data collected using the smart shoes, the gait parameters from the smart shoes was compared to the Qualisys motion capture system. The foot velocity algorithm was used to estimate HC and TO [1].

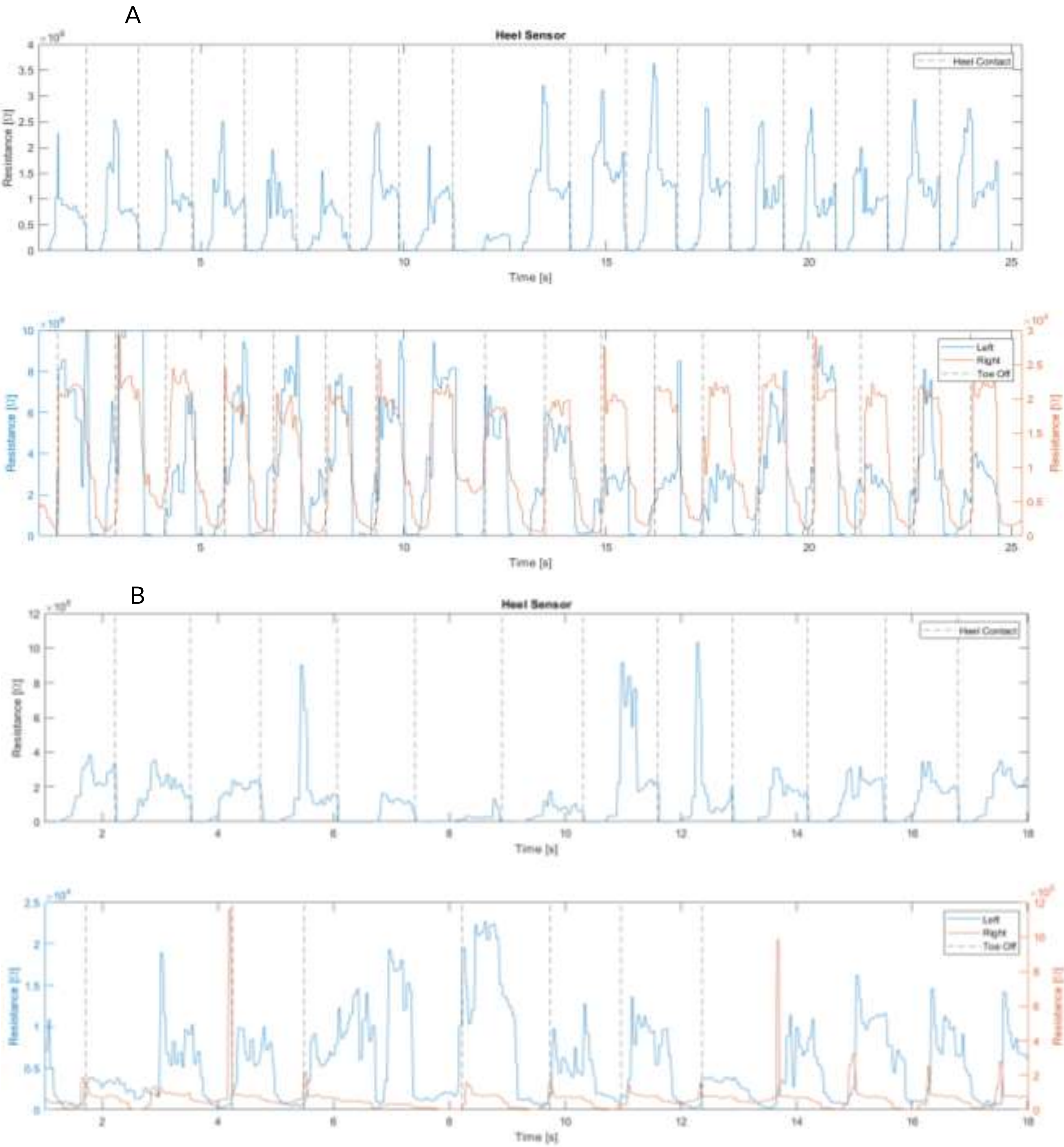

Figure 5: (A)Left shoe, (B)Right shoe. Identified HC and TO.

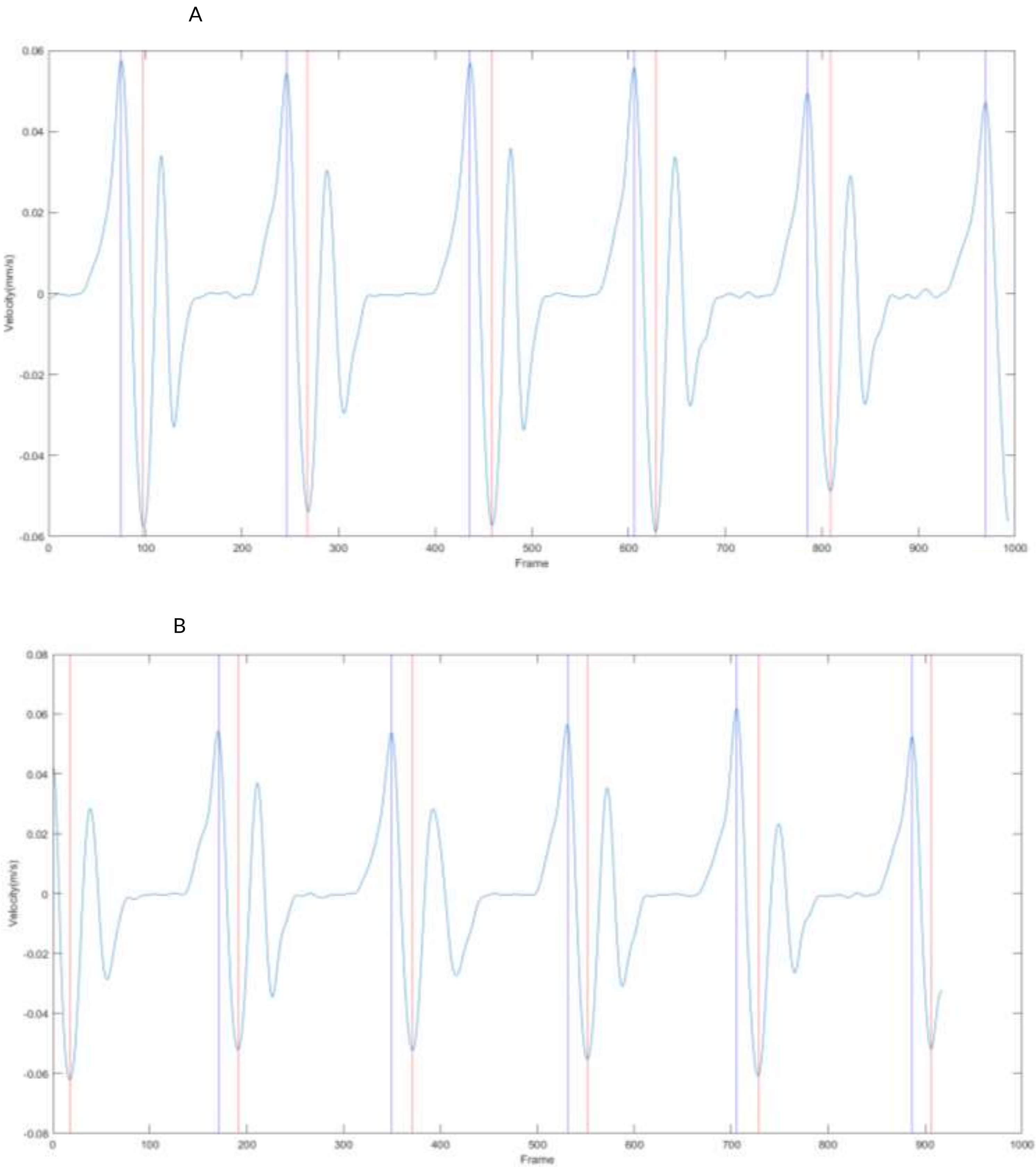

Figure 6: (A)Left mocap, (B)Right mocap. Identified HC (red line) and TO (blue line).

Tables 1A, 1B, 2A and 2B show results of the walking trials of a single subject. The mean stride, stance and swing times were calculated.

The overall mean was calculated for both shoes and motion capture and the mean error was calculated (**motion capture time – shoe time**).
Stride had the smallest mean error for both left and right. The toe-off is always earlier than the genuine toe-off, as the stance time from the shoe being shorter consistently than the motion capture (positive error), and the swing time being consistently longer (negative error), as seen in table 4.

		Stride Time	Stance Time	Swing Time
LEFT	Mean Error [s]	0.18845671	0.6856284	-0.42314314
	Percentage Error [%]	11.0903489	46.308365	189.628809
RIGHT	Mean Error [s]	0.2261433	0.6619286	-0.412724
	Percentage Error [%]	13.242454	44.278274	194.5719

Table 4: Error between mocap and shoe

Stride time had a small percentage error, whereas stance and swing were larger. This is likely due to the inaccuracies when estimating toe-off with the shoe. Swing had the largest percentage error, this is likely due to the swing having a negative mean error and a smaller mean time, therefore creating a greater percentage error.

		Stride Phase	Stance Phase	Swing Phase
LEFT	Shoe [%]	105.1025	55.2036	44.7964
	MOCAP [%]	99.75544	86.87447	13.12553
RIGHT	Shoe [%]	101.5078	57.17699	42.82301
	MOCAP [%]	100.0363	87.53051	12.46949

Table 7: Percentage of gait phases

Tables 5A, 5B, 6A and 6B shows the percentages of the gait phases.

The stride percentage for left and right shoe are above 100%, whereas the mocap value is closest to 100%, showing the mocap values are more accurate than the shoe. The stance to swing ratio for left and right shoe are 55:44 and 57:42. Whereas the stance to swing ratio of left and right mocap are 86:13 and 87:12, showing a difference of 30-31% between the shoe and motion capture.

According to the book 'Modern Method for Affordable Clinical Gait Analysis', the ratio of stance: swing phase is 62:38, this value is closest to the shoe data.

A possible reason the motion capture has a longer stance phase could be because the markers are placed at the back of the heel instead under the sole of the heel and, the toe marker is placed on the front tip of the toe instead at the ball of the toes. Therefore, the motion capture has an earlier heel contact and later toe off resulting in a longer stance time and shorter swing time. In comparison, the shoe has a later heel contact and earlier toe off, resulting in a shorter stance time and longer swing phase.

4.2 Step Time

- Step time: time between two consecutive heel strikes of the contralateral foot.

The data is cropped to align the right and left smart shoe and calculate the difference in times of the start of the left and right heel strikes.

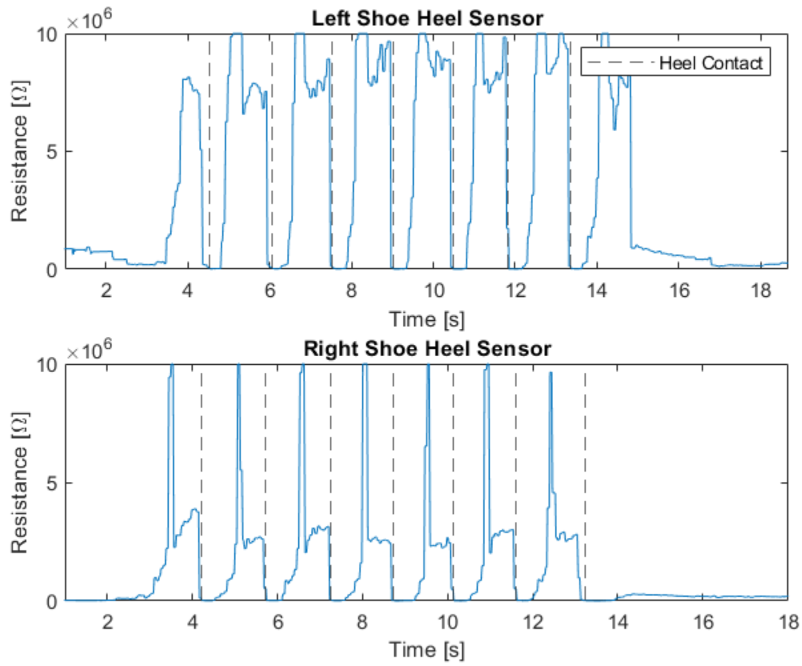

Figure 7: Identified heel contact in left and right smart shoes.

Time [s]	Heel Strike	
Left Shoe	Right Shoe	Difference (Step Time)
4.5247	4.2027	0.3220
6.0481	5.7286	0.3195
7.5283	7.2658	0.2625
9.0108	8.7235	0.2873
10.4725	10.1278	0.3447
11.8332	11.6107	0.2225
13.3534	13.2309	0.1225

Table 8: Smart shoes heel strike.

Time [s]	Heel Strike	
Left MOCAP	Right MOCAP	Difference (Step Time)
1.98	1.30	0.68
3.34	2.66	0.68
4.67	4.01	0.66

Table 9: Motion capture heel strike.

The average step time of the smart shoe is 0.268, whereas the average step time for the motion capture is 0.673. Therefore, there is a difference of 0.405 between the smart shoe and motion capture system. This could be since the motion capture system and smart shoe recordings were taken separately. Whereas, if the motion capture system and smart shoe data are collected at the same time more accurate data could be analysed.

5 Future Work

[1] The right and left shoe data need to be aligned to calculate the time difference between the heels strikes and toe-off.

[1a] Include the general step time for reference.

[1b] To receive more accurate data collection, the motion capture system and smart shoe recordings need to be taken at the same time, instead of separately.

[2] Need to take into consideration the sensor positions of the smart shoes which may be causing later heel strike readings and earlier toe-off readings.

[2a] Functions in MATLAB could be added to give more accurate stance and swing times.

[3] More data collection with several participants.

References

[1] C. M. O'Connor, S. K. Thorpe, M. J. O'Malley, and C. L. Vaughan, "Automatic detection of gait events using kinematic data," Gait & Posture, vol. 25, no. 3, pp. 469–474, 2007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0966636206001068

[2] Nandy, A., Chakraborty, S., Chakraborty, J. and Venture, G. (2021). *Modern methods for affordable clinical gait analysis : theories and applications in healthcare systems*. London, United Kingdom ; San Diego, Ca, United States: Academic Press, An Imprint Of Elsevier.

Appendices

Table 1A

SHOE LEFT	Stride Time		Stance Time		Swing Time	
Trial	Shoe Mean	Shoe sd	Shoe Mean	Shoe sd	Shoe Mean	Shoe sd
1	1.4057	0.3969	0.7247	0.05588	0.5944	0.0504
2	1.4822	0.0812	0.8431	0.1492	0.6628	0.0916
3	1.5397	0.8346	0.7763	0.0579	0.5593	0.0579
4	1.5792	0.5135	0.7824	0.1012	0.6668	0.1140
5	1.4716	0.3496	0.7922	0.0531	0.5944	0.0593
6	1.6255	0.4194	0.8950	0.2641	0.7290	0.2288
7	1.4719	0.0589	0.7509	0.0700	0.7173	0.0563

Table 1B

SHOE RIGHT	Stride Time		Stance Time		Swing Time	
Trial	Shoe Mean	Shoe sd	Shoe Mean	Shoe sd	Shoe Mean	Shoe sd
1	1.3222	0.0741	0.7399	0.0867	0.5952	0.0702
2	1.4836	0.0700	0.8424	0.0429	0.6448	0.0429
3	1.3520	0.1326	0.8028	0.0250	0.5428	0.0447
4	1.4767	0.0974	0.8702	0.0633	0.6303	0.0932
5	1.4693	0.4136	0.8076	0.0334	0.5881	0.0383
6	1.7860	0.1177	0.9192	0.0000	0.7322	0.0674
7	1.4812	0.0546	0.8489	0.0731	0.6405	0.0284

TABLE 2B

MOCAP LEFT	Stride Time		Stance Time		Swing Time	
Trial	Mocap Mean	Mocap sd	Mocap Mean	Mocap sd	Mocap Mean	Mocap sd
1	1.6625	0.053774	1.4580	0.060581	0.214	0.011402
2	1.8600	0.145831	1.6420	0.135536	0.232	0.008367
3	1.7775	0.103722	1.5600	0.087464	0.228	0.008367
4	1.6400	0.042426	1.4140	0.034351	0.224	0.008944
5	1.5700	0.073937	1.3500	0.069761	0.218	0.008367
6	1.655	0.042032	1.4275	0.045735	0.228	0.004472
7	1.7300	0.064807	1.5125	0.068981	0.218	0.004472

TABLE 2A

MOCAP RIGHT	Stride Time		Stance Time		Swing Time	
Trial	Mocap Mean	Mocap sd	Mocap Mean	Mocap sd	Mocap Mean	Mocap sd
1	1.6580	0.046043	1.4420	0.041473	0.216000	0.008944
2	1.9025	0.149304	1.6800	0.136382	0.218000	0.017889
3	1.7750	0.036968	1.5660	0.033615	0.210000	0.015811
4	1.6300	0.02582	1.4200	0.024495	0.210000	0.007071
5	1.5700	0.040825	1.3525	0.035940	0.217500	0.005000
6	1.6725	0.065511	1.4600	0.066833	0.210000	0.007071
7	1.7460	0.095289	1.544	0.095551	0.203333	0.010328

TABLE 3

	STRIDE			STANCE			SWING		
	Shoe overall Mean	mocap overall mean	Mean ERROR	Shoe overall Mean	mocap overall mean	Mean ERROR	Shoe overall Mean	mocap overall mean	Mean ERROR
LEFT	1.510829	1.69928571	0.18845671	0.794943	1.4805714	0.6856284	0.646286	0.22314286	-0.42314314
RIGHT	1.481571	1.70771430	0.22614330	0.833000	1.4949286	0.6619286	0.624843	0.21211900	-0.41272400

TABLE 5A

SHOE LEFT			
Trial	Stride %	Stance %	Swing %
1	106.5651	54.93897	45.06103
2	98.42619	55.98645	44.01355
3	115.2815	58.12369	41.87631
4	108.9705	53.98841	46.01159
5	106.1301	57.13255	42.86745
6	100.0924	55.11084	44.88916
7	100.2520	51.14426	48.85574

TABLE 5B

SHOE RIGHT			
Trial	Stride %	Stance %	Swing %
1	99.03378	55.41907	44.58093
2	99.75793	56.64336	43.35664
3	100.4756	59.66112	40.33888
4	98.41386	57.99400	42.00600
5	105.2733	57.86344	42.13656
6	108.1507	55.66186	44.33814
7	99.44944	56.99611	43.00389

TABLE 6A

MOCAP LEFT			
Trial	Stride %	Stance %	Swing %
1	99.43182	87.20096	12.79904
2	99.25293	87.62006	12.37994
3	99.41275	87.24832	12.75168
4	100.1221	86.32479	13.67521
5	100.1276	86.09694	13.90306
6	99.96980	86.22773	13.77227
7	99.97111	87.40248	12.59752

TABLE 6B

MOCAP RIGHT			
Trial	Stride %	Stance %	Swing %
1	100.00000	86.97226	13.02774
2	100.23710	88.51423	11.48577
3	99.94369	88.17568	11.82432
4	100.00000	87.11656	12.88344
5	100.00000	86.14650	13.85350
6	100.14970	87.42515	12.57485
7	99.92371	88.36324	11.63676