5
Development of the instrumented chair for the iSTS

5.1 INTRODUCTION

This chapter includes sections on the details of development of an instrumented chair that is used in some of the subsequent studies.

5.2 DEVELOPMENT OF THE INSTRUMENTED CHAIR

The development of instrumented chair used in this thesis took place in two iterations. The first version was used in all studies reported in the thesis and is described in detail in the following section. A description of another version of proposed chair is provided at the end of this chapter.

5.2.1 Initial Prototype of the Instrumented STS Chair

Development

The first prototype was developed using a solid wooden chair with four load cells each of which was rated for 40 kg with a precision of 8 g (CZL 601, Standard Load Cells, Vadodara, Gujarat, India). The four load cells were positioned in a cross, with a distance of 31 cm between each adjacent pair of load cells(Figure 5.1, a). This cross was then fixed on the seat of the chair and covered by an additional piece of wood (Figure 5.1, b). Each pair of load cells on one side of the chair was connected to a 24-bit analogue to digital converter (ADC) (HX711 Avia Semiconductors, Xiamen, China), with each ADC placed on a bracing strut on the side of the chair in which it was located (Figure 5.1, c). This model of ADC has an 80 Hz sample frequency that is fixed by an external 11.0592 MHz crystal. The two ADC receiving signals from the left and right load cells were connected to a microcontroller board (Arduino Mega 2560, Arduino LLC, Somerville, MA, USA), with data acquired using a custom-built software program written in Python. Data from the instrumented chair thus contained force data from each of the four sensors at 80 Hz. The instantaneous position of the CoP (Center of Pressure) of the forces applied through the chair was defined as the barycentre of the four vertical ground reaction forces measured by the load cells. Measurements of displacement AP and ML were calculated using the same method. Vertical ground reaction force Fz was taken as sum of the four ground reaction forces measured by the individual load cells (Figure 5.2.

Validation

The performance of the initial prototype to detect STS duration is described in detail in Chapter 7. However, prior to this study in which the performance of the iSTS Chair was compared to other instrumented testing systems, a validation was required to ascertain that the chair was able to accurately detect the STS movement. This validation used a force plate system, similar to that used in previous instrumented STS studies [Lindemann *et al.* [2003]].

5.2.2 Phase one

There were two separate tests performed, one with the chair placed on the force plate and other with the chair on the floor and feet on the force plate. The subjects were instructed to lift their

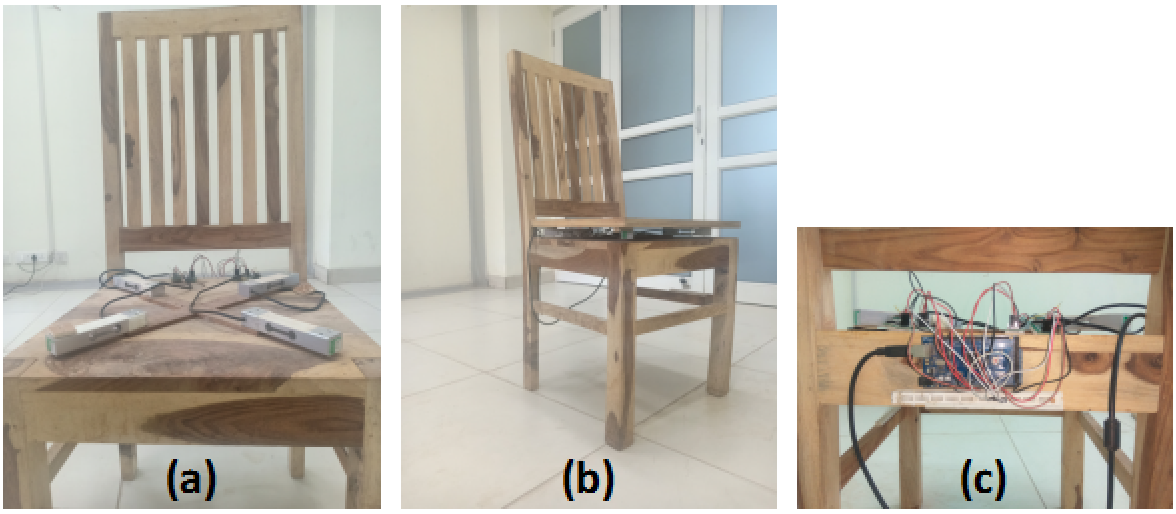

Figure 5.1 : (a) Placement of the load cells in a cross with the distances on the seat of the chair. The distance between the load cells is 31cm along front, back and both sides of the chair. (b) The load cells are covered by an additional piece of wood on which people can sit. (c) The ADC card attached behind the chair.

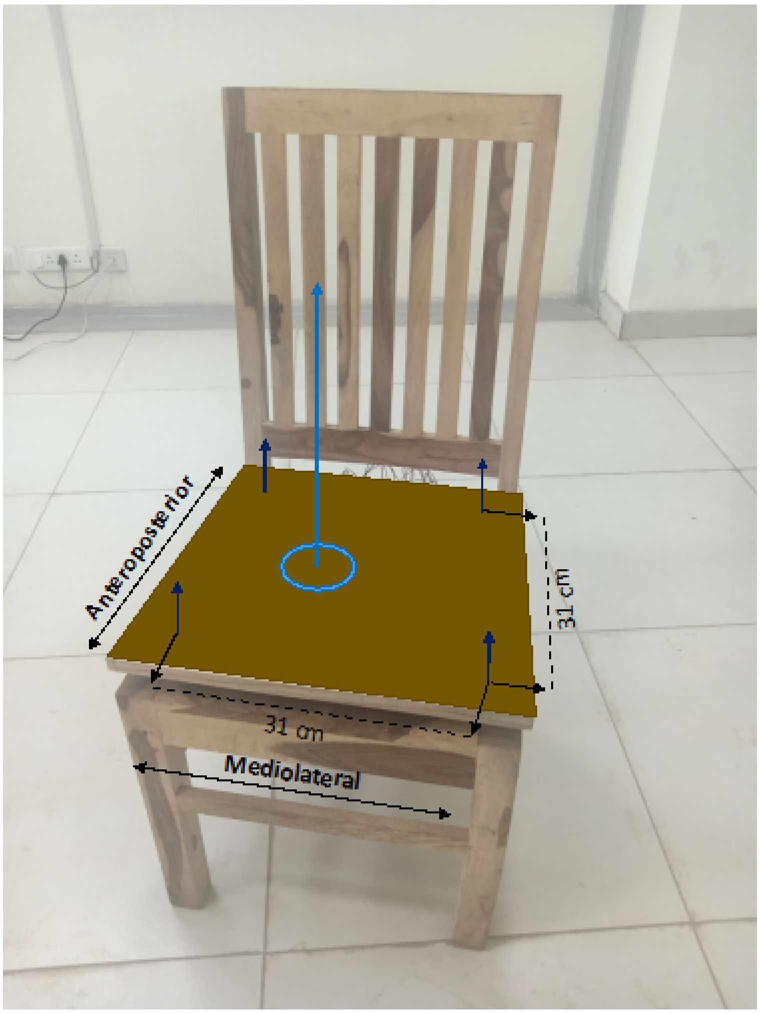

Figure 5.2 : Signals obtained from the load cells on the instrumented chair

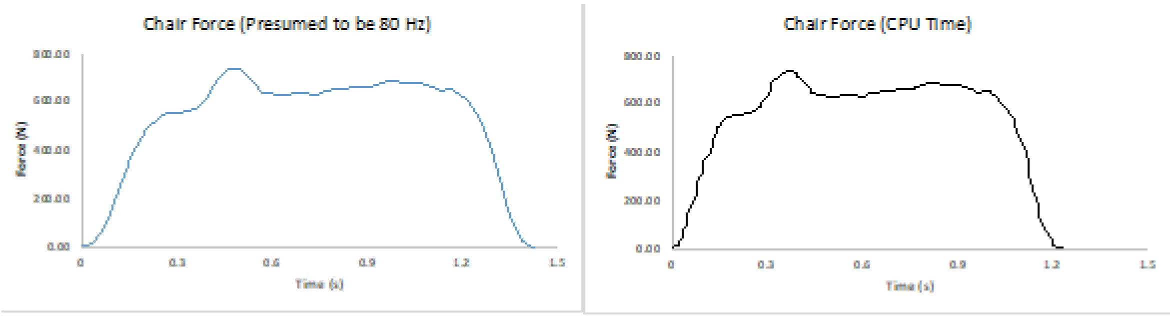

Figure 5.3 : Data from a single STS plotted versus assumed 80 Hz sampling frequency (left) and the CPU time-stamps (right)

feet off the ground in between each STS to enable detection of the different phases. Both tests were used to compare performance on the two systems.

Chair on the ground - feet on the force plate (CG-FFP)

There were 1792 lines of data from the chair, and 1988 lines of data from the force plate. Given the known sample frequency of 100 Hz for the chair, this gives a test duration of 19.88 sec for the force plate. Given the estimated sample frequency of 80 Hz for the chair, this equates to a signal length of 22.40 sec.

Chair on Force Plate (CFP)

There were 1796 lines of data from the chair, which is supposed to be recorded at 80 Hz, and 1979 lines of data from the force plate, which is known to be at 100 Hz. This gives a test duration of 19.79 sec for the force plate and 22.45 sec for the chair.

5.2.3 Analysis

The analysis had two parts, beginning with a comparison between the estimated 80 Hz sample frequency for the chair and the CPU time stamps provided for each line of data. The second part of the analysis was the synchronisation between the chair and the force plate for the series of STS performed. Data from the CG-FFP test was used for this analysis.

CPU Time The time gap between each pair of successive points according to the CPU clock data averaged 0.0115 seconds, which equates to a sample frequency of 87.2 Hz. However, the standard deviation of the time between successive points was 0.008 seconds, which equates to a coefficient of variation of 69.3%. This was due to a large number of successive points having the same CPU time, thus giving a gap of 0 seconds, something which occurred 27.2% of the time. There were also 44.1% of gaps of 0.016 seconds, which equates to 62.5 Hz and 26.3% of gaps of 0.015 seconds, which equates to 66.7 Hz. In total, 97.7% of gaps between successive points was either 0, 0.015, or 0.016 seconds.

When two successive lines of data were shown as arriving at the same time (same CPU time), it is possible that they were acquired at the correct sample frequency but time-stamped at the same time by the PC. To verify this, the 3rd STS was used, which was the smoothest of the five STS performed. This 3rd STS is shown in Figure 1 for both 80 Hz and CPU times. It can be seen that the plot for force against an assumed 80 Hz sampling frequency produced a smoother curve than that of the CPU time.

The two occasions when consecutive samples showed the greatest rate of force development (RFD) in the sitting down and standing up phases were chosen and presented in Table 5.1 for the

Table 5.1 : Rate of force developement for estimated 80 Hz sampling frequency

	Time	Force	RFD
Sitting down 1	0.1000 0.1125 0.1250	184 229 275	3617 3637
Sitting down 2	0.1375 0.1500 0.1625	318 359 396	3267 2981
Standing up1	1.2875 1.3000 1.3125	418 362 300	-4509 -4903
Standing up2	1.3250 1.3375 1.3500	239 181 130	-4603 -4088

Table 5.2 : Rate of force development for CPU time stamp estimated sampling frequency

	Time	Force	RFD
Sitting down 1	0.0000 0.0150 0.0150	184 229 275	3014 N/A
Sitting down 2	0.0000 0.0000 0.0240	318 359 396	N/A 1553
Standing up1	1.0000 1.0160 1.0160	418 362 300	-3523 N/A
Standing up2	1.0000 1.0160 1.0160	239 181 130	-3596 N/A

estimated 80 Hz sampling frequency and in Table 5.2 for the CPU time stamp estimated sampling frequency. Consistent RFD is evident for all samples when 80 Hz is assumed, however, from the CPU time it is clear that this method of estimating sampling frequency is not valid and should not be used for any subsequent data collection, with some values unable to be counted due to identical time values being reported for some frames.

5.2.4 Synchronisation

For these calculations the sample frequency of 80Hz was chosen rather than CPU time after the results of the previous test. The full recording from both the chair and the force plate for the recording configuration with the feet on the force plate and the chair on the ground is shown in Figure 5.4.

In this configuration, the start of the STS for the chair data was taken to be the time when force began to decrease rapidly, signifying that the person was starting to stand up Figure 5.5, left). The standing phase of the STS was taken to be the period when there was no force recorded from the chair, while the end of the STS was taken to be the first peak in the force signal after a standing phase. With respect to the force plate, the start of the STS as taken to be the time when force began to increase, signifying that the person was starting to transfer their weight to the force plate (Figure 5.5, right). The standing phase of the STS was taken to be the period between the peak force after the person stood up, and the peak force indicating that the stand-sit phase had begun.

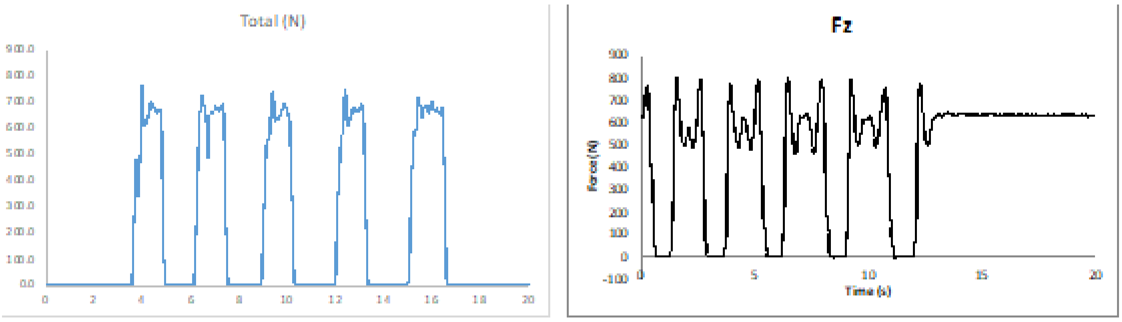

Figure 5.4 : Data from the chair (left) and force plate (right) with the feet on the force plate and the chair on the ground.

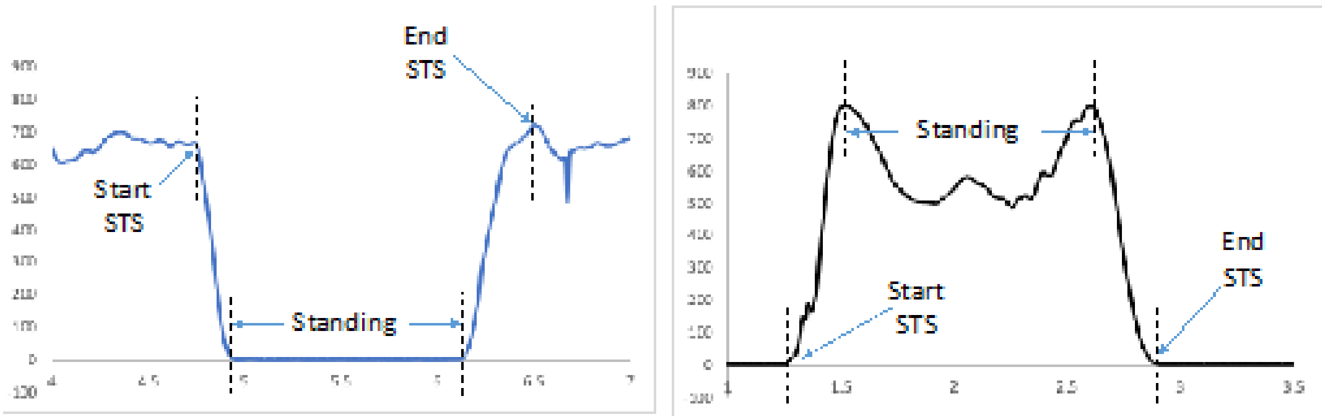

Figure 5.5 : Identification of a single STS for the chair (left) and force plate (right) with the feet on the force plate and the chair on the ground

Table 5.3 : Comparison of STS durations calculated for chair and force plate data.

	Chair		Force plate		Comparison	
	Points	Time	Points	Time	Delta (%)	Ratio
STS 1	142	1.775	166	1.66	6.9%	1.069
STS 2	167	2.088	192	1.92	8.7%	1.087
STS 3	198	2.475	216	2.16	14.6%	1.146
STS 4	190	2.375	219	2.19	8.4%	1.084

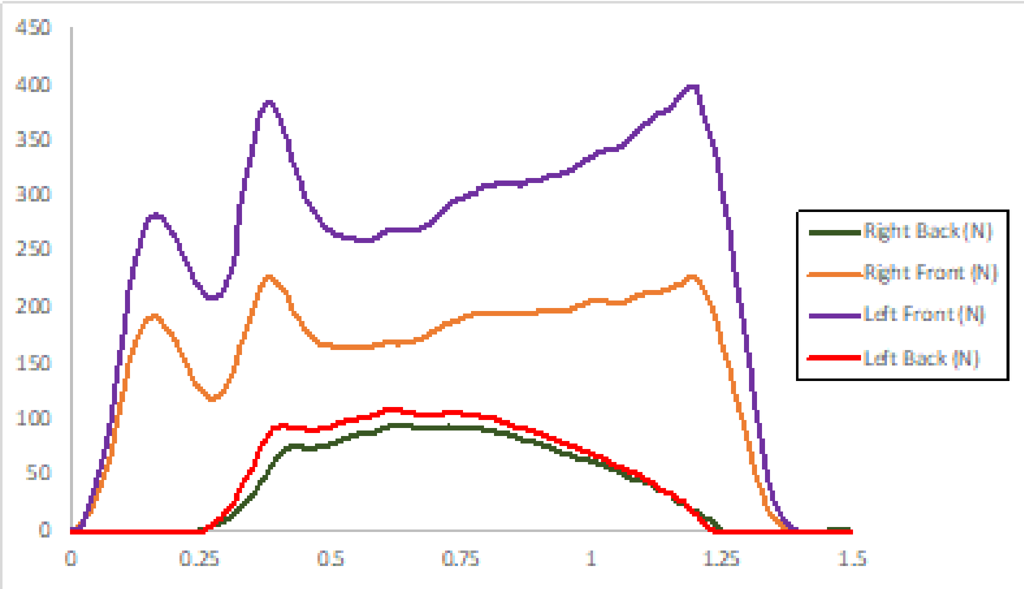

Figure 5.6 : Identification of a single STS for the chair (left) and force plate (right) with the feet on the force plate and the chair on the ground

An example of the signals obtained from a single STS movement for the chair is shown in Figure 5.6, with each individual sensor signal shown. It can be seen that each sensor presents a different signal, with the front sensors showing the first increase in force when the subject begins to sit down. A characteristic decrease in the force levels of the front two force sensors then occurs as the person transfers their weight towards the back of the chair, thus increasing the force recorded from the two sensors at the back of the chair.

The estimated start and stop for each of the four STS for both the chair and the force plate were calculated manually. The results of these calculations are in Table 5.3. The mean ratio between the two systems for the estimation of STS duration was 1.10 ± 0.03, with a corresponding coefficient of variation of 3.1%.

A second method was used to estimate the start and stop for each of the four STS for the chair using only the sum of the sensors at the front of the chair, rather than using the sum of all four force sensors. The results of these calculations are shown in Table 5.4. The mean ratio between the two systems for the estimation of STS duration was 0.96 ± 0.02, with a corresponding coefficient of variation of 1.8%.

Conclusion The chair sample frequency is likely to be close to the 80 Hz predicted, given the

Table 5.4 : Comparison of STS durations calculated for chair and force plate data using only the front sensors

	Chair		Force plate		Comparison	
	Points	Time	Points	Time	Ratio	Delta
STS 1	142	1.78	166	1.66	1.07	0.12
STS 2	167	2.09	192	1.92	1.09	0.17
STS 3	200	2.50	216	2.16	1.16	0.34
STS 4	190	2.38	219	2.19	1.08	0.19

Table 5.5 : Comparison of STS durations calculated for the five methods used

		STS Time (sec)				
Subject	Speed	Mobile Phone	JiK	Force Plate	Kinect Skeleton	Mobile RGB Skeleton
1_2	Fast	10.7	11.2	10.5	9.9	10.6
1_3	Slow	10.5	11.5	10.8	9.9	12.9
1_4	Fast	6.6	7.1	6.7	6.5	10.3
2_1	Slow	13.2	13.9	12.8	11.6	9.6
2_2	Fast	10.7	11.1	10.2	9.3	7.6
2_3	Slow	13.4	14.4	13.2	13.7	10.4
2_4	Fast	6.7	9.4	8.6	9.2	6.6
3_1	Slow	8.0	10.6	9.9	10.1	13.5
3_2	Fast	7.7	8.3	7.8	8.0	9.0
3_3	Slow	10.9	11.4	10.7	11.2	10.8
3_4	Fast	8.3	8.7	8.2	8.7	8.3

small coefficient of variation between the two trials. Accordingly, the next phase of testing will use the estimated sampling frequency of 80 Hz.

5.2.5 Phase Two

All tests were performed with the chair on the floor and feet on the force plate. Three people were tested a total of four times each, with two tests at fast speed and two tests at slow speed for the STS movement. The subjects were instructed to lift their feet off the ground in between each STS to enable detection of the different phases. Both tests were used to compare performance on the two systems. Data was recorded from both systems, with a video recording from a mobile phone used to manually verify the length of each the STS.

The length of the STS was estimated by detecting the start and end of the STS from the video recording, with an estimated rate of 30 frames per second (fps). The length of the STS estimated using the force plate and iSTS Chair used the method developed previously, as shown in Figure 5.6. The estimated start of the 1st STS and the end of the 5th STS, for both the chair and the force plate, were calculated manually based on this method, with the results of these calculations shown in Table 5.5. The first trial (slow) for subject 1 was discarded due to an erroneous line of data from the chair, with force changing from body mass to zero between consecutive lines, as shown in Figure 5.7below. This meant it was not possible to exactly calculate the duration for the STS due to the missing data. Data for all other trials showed no signs of any errors.

Times for the remaining 11 trials are shown in Table 1. There was good agreement between all methods except for the RGB skeleton using the mobile phone. Plots of the times obtained are shown in Figure 5.8.

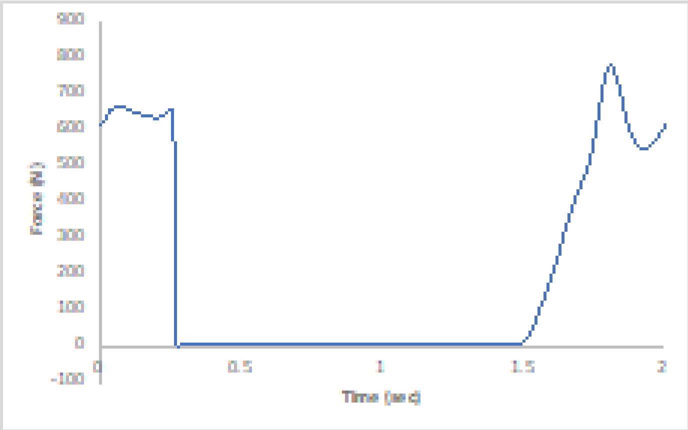

Figure 5.7 : Erroneous reading from the chair for subject 1(slow).

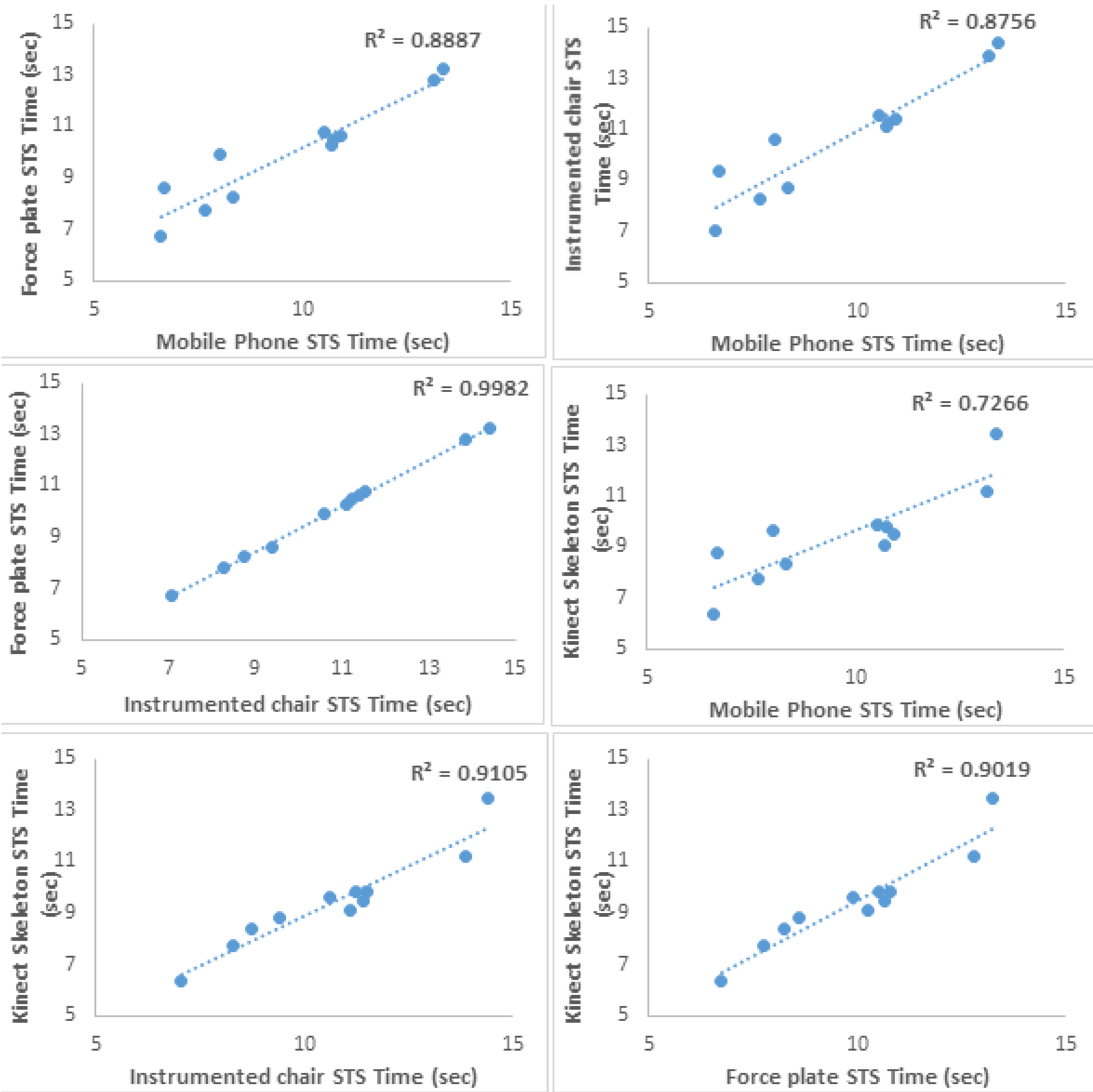

Figure 5.8 : Comparisons between the different measurement methods.

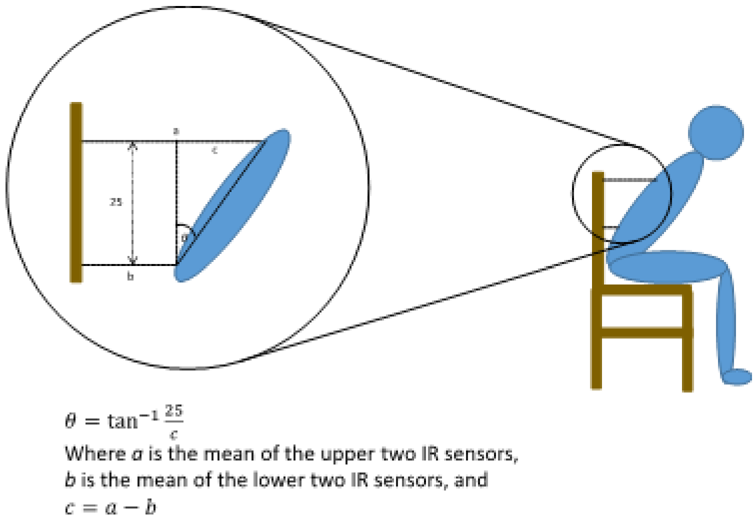

Figure 5.9 : Detection of trunk angle during the STS using an instrumented chair with infrared sensors

5.2.6 Conclusion

The iSTS Chair and force plate have excellent agreement in terms of identifying the STS. The use of centre of pressure data could be used to further improve results. A detailed evaluation of the performance of the iSTS Chair compared to the other mentions used in this preliminary analysis is described in detail in Chapter Six.

5.2.7 Second Prototype of the Instrumented STS Chair

One of the key requirements of the iSTS Chair is to be able to identify the different phases of the STS movement in order to be able to extract parameters specific to each phase of the movement such as velocity in the sit-to-stand phase. Although, some of these phases could be identified successfully using the initial prototype, in some cases additional information related to the position of the trunk was required. Furthermore, leg length is one of the variables included in the predictive equation developed by Takai et al. [Takai *et al.* [2009]].

As a result of these requirements, additional sensors needed to be added to the chair. This necessitated the development of a second prototype that is currently under construction. A description of these changes made is described in the remainder of this section of the methodology. This version of the chair uses the same chair as the initial prototype, but has five additional infrared (IR) sensors, all of which are directly acquired using the Arduino system at 80 Hz. In addition to the sensors, the chair has been made height-adjustable, in order to account for differences in leg length, which directly influences the power required to stand up from a chair [Schurr *et al.* [2012]].

Four IR sensors are placed in the back of the chair, as shown in Figure 6. One sensor faces towards the back of the person being tested and is used to measure the distance between the chair the person. The inverse tan rule is used to estimate trunk angle relative to the back of the chair, as shown in Figure 7. One IR sensor is placed underneath the chair and is used to estimate leg length. This sensor estimates the distance between the underside of the seat of the chair and the floor, with an adjustment made to this measurement to account for the thickness of the seat. Provided the person being tested is sitting with their thigh parallel to the ground, leg length can be estimated using chair height from the ground.

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