Design of a Dynamic Balance Assessment System

by

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I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Engineering is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my own work.

Signed: ____________ ID No.: 98040049

Date: 1-10-07

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I would like to express my profound gratitude to both of my project supervisors for their supervision, guidance and patience throughout my research.

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Finally I would like to thank my family and friends for their love and support throughout my studies.

DEDICATION

To my parents

Abstract

The aim of this work was to design, build and test a system that could perturb a test subject standing upon it in order to assess their ability to react to these changes. This would be achieved by rapidly tilting the surface on which the person was standing and then returning it to the horizontal position. From this it could be determined whether the test subject was able to maintain a state of balance or how long it took them to return to that state of balance. This state of balance would be determined by measuring the subject's postural sway by using a foot pressure profile plate to determine how much deviation there was during testing. This system was also designed to be more versatile and affordable than what is currently available commercially, as while these machines are important for studies they are not in common use at present due to their cost. The newly developed system presented in this thesis, has been used to move test subjects up to 100kg in weight.

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Chapter 1

Introduction

1.1 Introduction

This project arose as a result of the need to test balance in a dynamic situation with fully repeatable and reproducible conditions for each user. Most commercial balancing devices such as Balance Boards and Swiss Balls provide unstable surfaces which the test subject has to balance on. These devices provide an unstable surface with which the subject can interact and can be used for many basic exercises. The unstable surface forces the body to activate the smaller stabilizer muscles to maintain balance and through the unpredictability of this motion, it can mimic real life quite closely. Sports physiotherapists and medics use this type of device to test a person's ability to balance.

Typically in tests with these devices a perturbing force was provided by the assessor pushing the test subject. This does not however allow for a high degree of repeatability. One of the purposes for the device developed in this work was to introduce a greater degree of repeatability to balance related tests that rely on disturbing the subject's centre of balance and measure of the subject's reaction to this change to their centre of gravity. The use of this platform and its control program would enable the tester to reproduce the same perturbance to the subject's centre of gravity. This would eliminate one source of variance from this type of testing thereby improving the validity of results produced.

It was also necessary for the device to be able to be used in conjunction with the RSscan Foot Pressure Profile Measurement Mat which was available in the School of Health and Human Performance, DCU. The RSscan mat shows and records the changes in pressure of the surface in contact with it, in this case the test subject's feet. This allowed the tester to analyse subjects for a range of ankle, hip, and neurological problems affecting balance. It also allowed the testing of reaction times in athletes to see how quickly and efficiently they could cope with sudden changes in their centre of gravity. Assessment of the recovery ability from a fall in the elderly or disabled would also be possible with this device.

In addition to reproducibility of conditions it was also important that any perturbance to the subject could be sudden and unpredictable. If the motion was to continue in a regular pattern for a sufficient time period, it would activate the body's proactive responses as the subject began to predict the direction of the perturbances. In this case the muscles could be activated before the perturbances to minimise disturbances due to this expected motion. The system therefore had to be able to provide a surface on which the user could stand and which could be held steady, then actuated quickly and returned to the static horizontal position. The rapid tilting of the subject's base to a predetermined angle and subsequent return to the original horizontal position were used to cause a perturbance to the subject's centre of pressure. After perturbance the machine was to restore the test subject to a stable position while recordings would be made of the subject's reaction to the unexpected movement. A preliminary system design and characterisation thereof using motor actuated balance board tilting is presented in Chapter Two. The final system design and characterisation using pneumatic actuators is presented in Chapter Three.

The readings from the pressure plate on which the test subject stands were recorded at a rate of up to 500 Hz. Along with these readings the software also allowed the calculation of the centre of pressure of the subject and how this varied over time. It could also then be configured to display how far the subject strayed from their centre of balance during the test. The pressure readings were displayed in the form of a colour coded pressure distribution diagram, which allowed the changes in pressure to be displayed with time. This is discussed in more detail in Chapter Four in relation to a set of human performance trials that the system was used for. Chapter Five presents discussion and conclusions related to the performed work. An initial introduction to the work area is presented in the rest of this chapter.

1.2 Balance and the human body

1.2.1 Factors affecting balance

There are three main sensory systems used by the body in balance and postural control. They are the vestibular system, the somatosensory system (touch) and the visual system.

[1, 2] The Vestibular system is used by people to sense their posture even without being able to see any reference objects. It depends upon the fluid filled inner ear whose three separate chambers act somewhat like a spirit level to help the body to maintain balance without a visual reference.

The Somatosensory system is in part a touch based system which transmits cues as to the subject's environment through the skin. The soles of the subject's feet transmit information regarding the inclination of the surface upon which he is standing. This system also relies on "the mechanism involved in the self-regulation of posture and movement through stimuli originating in the receptors imbedded in the joints, tendons, muscles, and labyrinth" [3]. This refers to the fact that even without a visual reference the subject is aware of the position of their limbs and their relation to other body parts. Golgi tendon organs are a sensory receptor system used by the body in spatial awareness. They allow the body to judge with some accuracy where any one part of the body is, at any time, without using visual input and act as receptors to determine the body centre of gravity (COG) [4, 5, 6].

Finally, the Visual system uses sight to provide visual references of the body's current spatial orientation [7, 8]. Visual information stabilises posture by reducing the variability of the head's position in space and the position of the center of mass (COM) within the support surface defined by the feet. These three systems are all used together to help maintain an upright posture. Table 1.1 shows in more detail how they are used describing favorable and unfavorable conditions.

[10, 11] Postural sway refers to the motion, generally compared to the sway seen in an inverted pendulum that is generated by the body as it attempts to maintain an upright posture. These swaying motions are thought to be generated by the body's own control mechanisms as they attempt to correct any motions that could lead to loss of balance. It

is like a feedback loop based control system with the minor swaying motions like the minor oscillations that occur in these systems, attempting to correct a parameter that went beyond the limits predefined for it by the program. These control mechanisms provide postural control in response to the sensory input from the body's three main balance based sensory systems as outlined above.

Sensory system	Critical reference	Conditions favoring use	Conditions disrupting use
Somatosensory	Support surface	Fixed support surface	Irregular or moving support surface Sway-referenced support surface
Visual	Visual field	Earth-fixed visual surrounds with irregular or moving support surface	Moving visual surrounds Eye closure (darkness) Sway-referenced visual references
Vestibular	Gravity or inertial space	Irregular, compliant, or moving visual surrounds and/or support surface Darkness	Novel or unusual motion environments Changing gravitoinertial references

Table 1.1 Sensory systems used in balance [9].

The following is a list of characteristics used to quantify postural sway and postural control by one set of researchers [12]. In their work they used the standard deviation and range of

(1) anteroposterior sway of COG during each trial (duration 37 s, sampling rate 50 Hz);

(2) mediolateral sway of COG;

(3) angular motion of the right ankle angle defined by the foot, ankle and knee markers;

(4) angular displacements of the right hip angle in the sagittal plane defined from knee, hip and shoulder markers; and

(5) angular displacements of the right hip angle in the frontal plane defined from knee, hip and shoulder markers.

These measures of angular motion were chosen to obtain data for co-ordination of body parts in addition to COG motion data.

Postural control can be broken into two broad groupings - proactive control and reactive control. Proactive control is used by the body to maintain balance while performing regular tasks. A particularly relevant example of this would be the body's maintenance of an upright posture during quiet standing. Reactive control is used to counter unexpected disturbances to the body's centre of gravity. An example of this would be recovery of balance after tripping.

Proactive control and reactive control were described in an article from Molson Medical Informatics [13]. In this article, they indicate that the body centre of mass is outside the base of support 80% of the time during walking. The body has two methods of controlling this dynamic equilibrium. The first of these is reactive and the second is proactive. Unexpected perturbances to balance are controlled by the bodies reactive control mechanism with the aid of sensory inputs. Proactive control on the other hand controls balance during the normal gait cycle of the body. This includes the use of the vision system to take account of upcoming disturbances to the normal gait cycle.

Black et. al investigated the reactive control system and used this to draw conclusions about the ankle joint [14]. In their work, they used muscular coordination tests to record patient's reactions to unexpected disturbances. This provided information regarding the ankle joint torque response, strength and symmetry between the two legs. It was noted from their work that extended latencies can indicate spinal cord segmental pathway, cortical abnormalities, or orthopedic problems.

Frontal sway is the amount of sway in the body along the frontal plane while in any stance. Sagittal sway is the amount of sway along the sagittal plane. These planes are depicted in Figure 1.1.

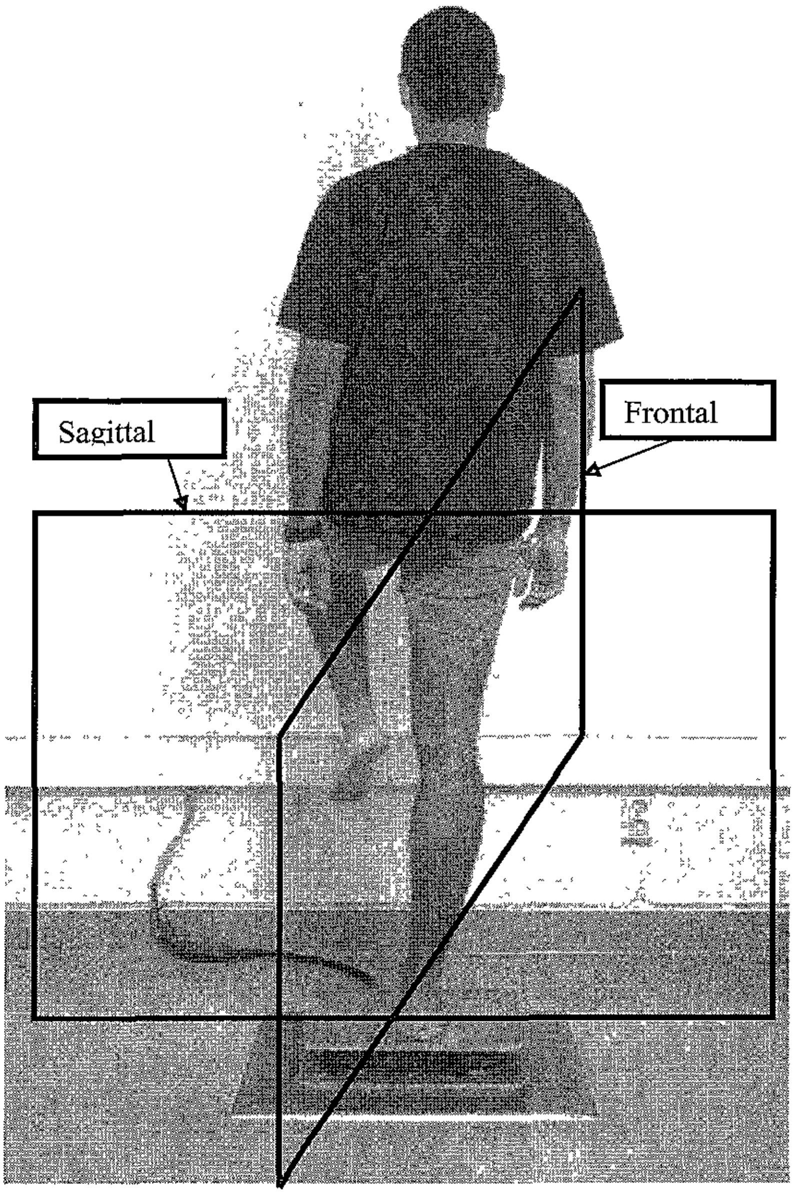

Figure 1.1 Frontal and sagittal planes [15].

Figure 1.2 shows some of the different stances and how these can affect balance along the frontal and sagittal planes. A two legged stance such as is shown here is common in balance related tests and information on expected levels of sway would be important in tests such as these.

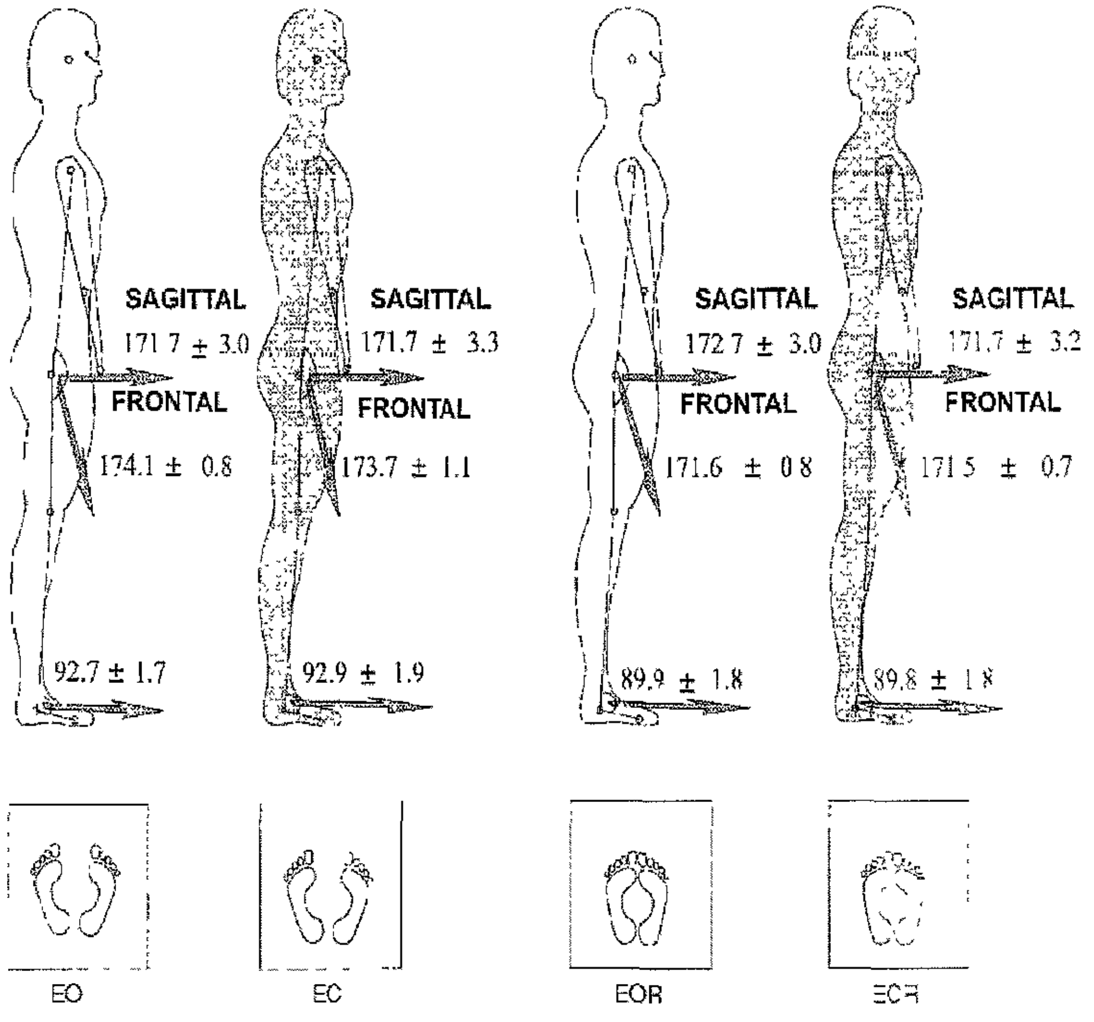

Figure 1.2 Stance and sway affecting centre of pressure [16].

Figure 1.3 illustrates the body's response to a loss of balance. Figure 1.3 (a) and (b) show the stretch reflex in the muscle that counteracts the loss of balance. Figure 1.3 (c) and (d) illustrate the balance correcting response and how it corrects the over compensation of the stretch reflex of the postural control muscles. This indicates that the body has an automatic balance control mechanism which is in turn managed by a more sophisticated feedback based control mechanism. This has been shown in numerous studies two examples of which are [17] and [18]. The balance platform designed in this project was used in tests that allowed examination of these body balance corrections.

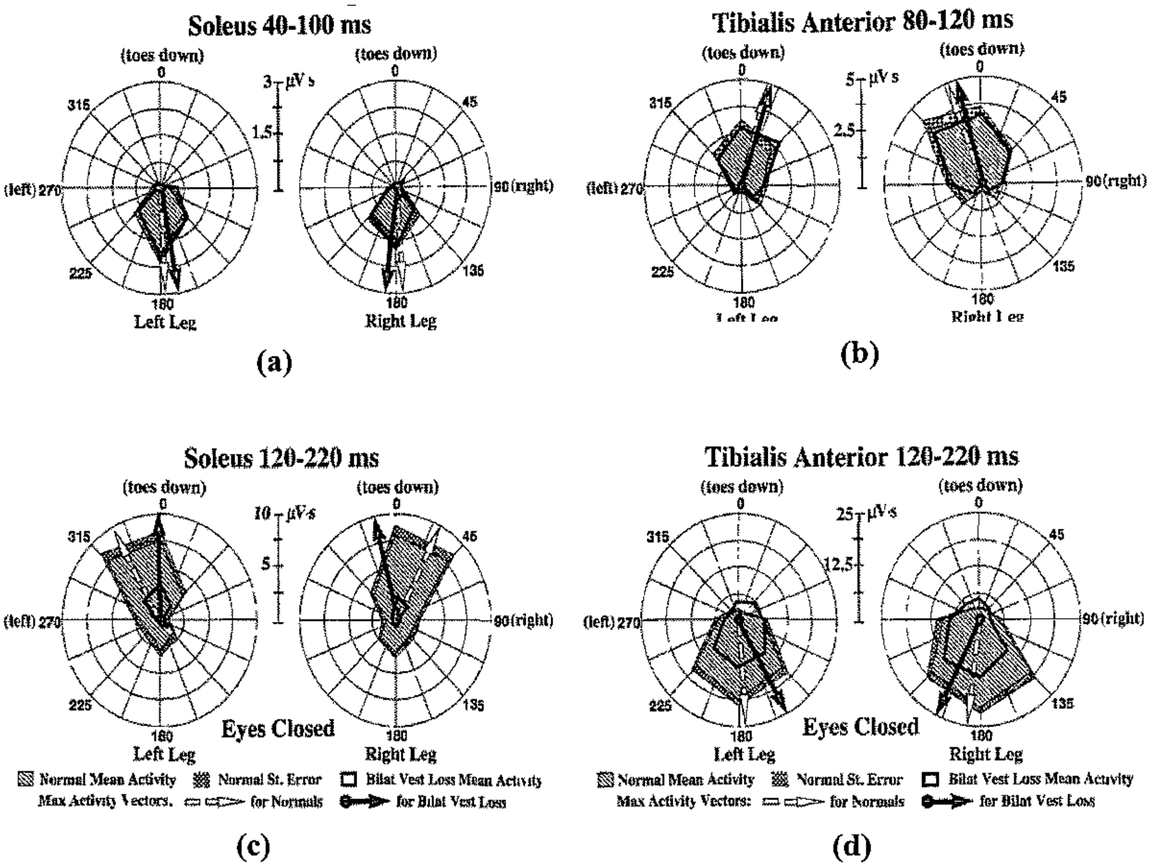

Figure 1.3 Multi-planar tilting postural responses (a) stretch reflex response for soleus muscle, (b) stretch reflex for tibialis, (c) balance correcting response for soleus, and (d) balance correcting response for tibialis [19].

1.2.2 Balance tests

Various tests have been used in the assessment of balance in the human body. While these tests cannot quantify the test subject's balance they can quantify parameters related to balance. Some of these parameters are *postural sway*, which can be broken down into a frontal and sagittal sway component.

One commonly used assessment in balance analysis is the Romberg test. This originated from work by Martiz Heinrich Romberg in 1853. During this test the subject has their eyes closed. This test has the subject standing in various stances while a force is applied to upset their balance. The first of these involves the subject standing in a shoulder width stance and attempting to maintain balance as the tester subjects him to a range of perturbances. The test is then repeated with the subject standing on first one foot and then the other and again being subjected to the same range of perturbances. The intended outcome of this test is an assessment of the point at which the subject is no longer able to maintain his balance. The subject can be classified according to postural sway and the extent of his deviation from normal healthy balance. Classification is determined from the last completed test for which the subject was able to maintain balance. Variations include standing on softer and so less stable surfaces e.g. a foam pad, thus providing an even steeper challenge [20].

One of the problems with this test was that the force being applied to the person was applied by a human source and so was subject to deviation. This can lead to inconsistencies in results with subjects for example failing prematurely due to excessive force being applied in a particular push. Further information on the Romberg test can be found in Appendix A.

The balance board on the other hand, allowed the same degree of perturbance to be produced every time. In a balance board system the subject stands on a top plate which is tilted. The degree of perturbance could be increased by increasing the angle of tilt, the only limits being the angle through which the Top Plate could move and the point at which friction between the Top Plate and the subject was no longer sufficient to prevent the subject from sliding.

Figure 1.4 shows an example of the results taken from the pressure mat during the human performance trials conducted during the compilation of this thesis to analyse balance during a single legged stance. These results are discussed further in Chapter Four.

Figure 1.5 shows a 3D model of foot profile pressure distribution. This shows a topographical representation of the distribution of the subject's weight through his feet. This type of representation makes it easy to determine high pressure regions and so gauge the subject's weight distribution and its change over time. This was used in a study comparing walking differences in the young and the elderly and aided in the speedy identification of differences between the two subject groups [21].

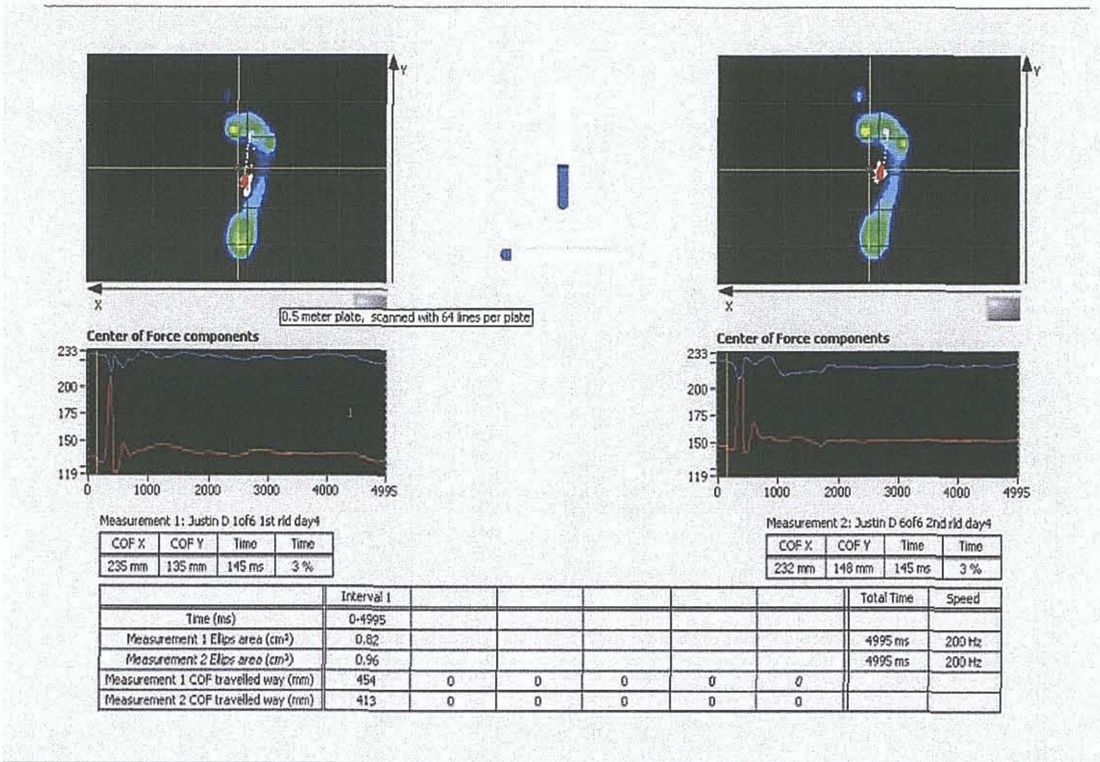

Figure 1.4 Normative sway seen during one legged stance.

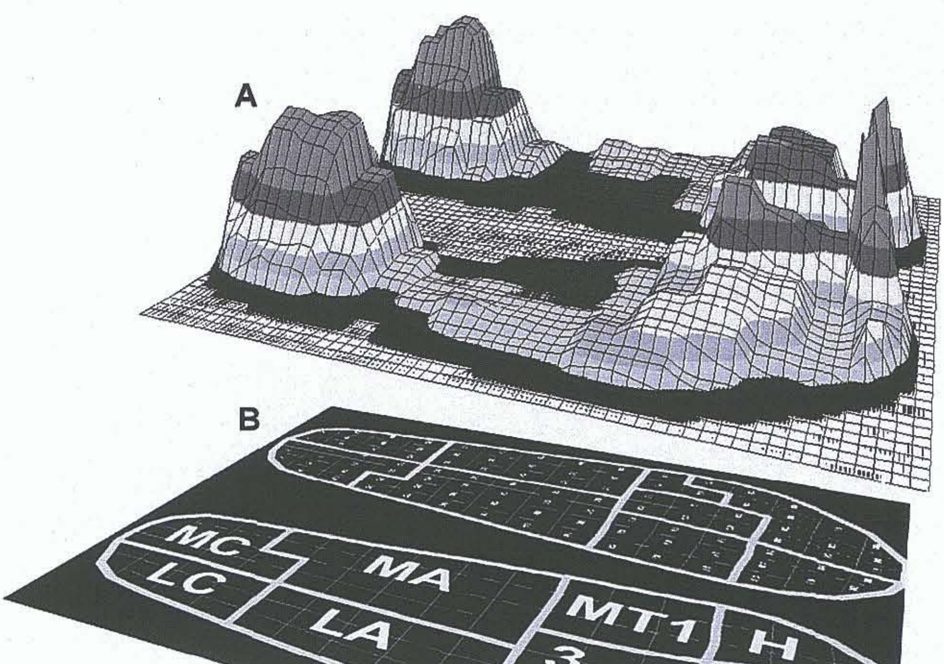

Figure 1.5 Methods of foot pressure measurement [22]

It has been shown that when controlling balance the postural sway of the body can be represented by the motion of an inverted pendulum [23]. Figure 1.6 shows the inverted pendulum representation of the ankle joint and also indicates the stretch reflex control of the ankle joint. This sway value can be used to indicate the level of balance of a particular test subject as at present it is not feasible to accurately quantify the subject's level of balance. This postural sway value can be calculated by using a pressure profile mat to measure the change in the subject's centre of pressure over time in both the frontal and sagittal planes [24]. Overall (OA), anteroposterior (AP), and mediolateral (ML) indices are used to measure postural stability. A high score in the OA index indicates poor balance. The patient's ability to balance is believed to be best indicated by the OA index.

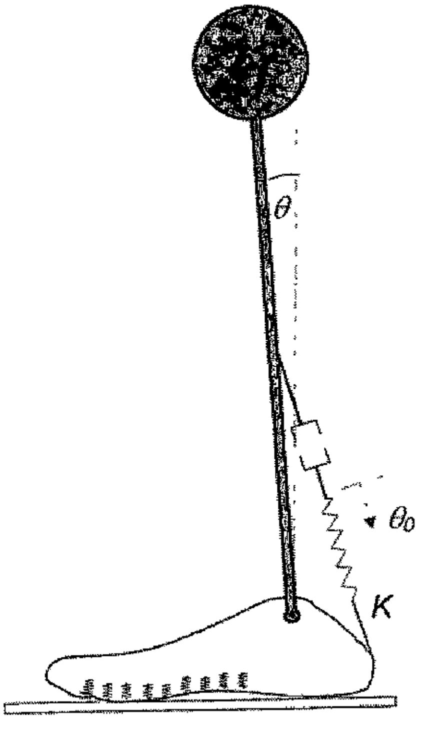

Figure 1.6 Ankle joint biomechanics [25].

1.3 Balance and health

1.3.1 Areas benefited by balance assessment and training

The design and construction of balance platforms allows them to be used in the testing of sports people, the injured, those with other motion related disabilities, diabetics, the elderly, suffers of neurological disorders such as Parkinson's disease and stroke victims [26]. The platform can also be used as an early detector of various conditions including schizophrenia, Parkinson's and other neurological impairments. Investigation of reaction time latencies for the major muscles (times measured typically in ms) can be done by changing the direction in which the subject stood. For example if the person were to stand facing perpendicular to the direction of tilt, the reactions in the ankles and adductors can be assessed. If positioned in line with the plane of tilt then the ankles and the hamstrings or quadriceps are assessed.

When evaluating subjects with neurological deficits, Clinical Balance Scores, also known as Stabilometry Scores for other tests, are used as the measure of Postural Stability within the patient. Another grouping of subjects that could benefit from the use of this balance system is athletes [27]. Athletes can have their balance and reaction times assessed using Stabilometry Scores to quantify the levels of improvement they are receiving from their training if any. This is an area that is difficult to quantify and measure by other means. Although strength, speed and endurance can be quantified, measurement of reaction time is more difficult. Athletes can also be tested to determine the likely hood of injuries such as ankle injuries [28]. As well as this, this balance board can be used in training to accustom the athletes to rapid changes in centre of gravity and improve balance especially for contact field sports. When contact sport athletes are competing, (judoka, rugby players, etc.), they must react to outside events interfering with their centre of gravity, i.e. their opponents. This is a prime aspect of their sports and of major concern at any level to them. It helps in injury prevention as well as their success at their sports.

Studies have been conducted into whether balance testing can be used to differentiate between patients who have had an ankle injury 12 months previous and those without an injury [29]. It was found that one in four of the patients that had an ankle fracture operated on showed decreased control compared to an age and gender matched equivalent.

Diabetic patients could also benefit from having an improved testing method for studies into how diabetic neuropathy leads to the decrease of rapidly available ankle strength, thus hindering balance recovery. Neuropathy causes a distal impairment in lower extremity sensory function which can increase fall risk [30, 31].

Research has also shown a link between balance related issues and schizophrenia. It has been hypothesized that this difficulty with postural control is due to an underlying disruption of the patient's cerebellar function. Posture is to a large extent controlled by the cerebellum. It was found that schizophrenic patients had showed definite disturbances to postural control and balance [32].

There is evidence that supports the hypothesis that older adults have difficulty managing the mechanical energy introduced to the system during various activities or in detecting perturbations [33 - 38]. Older adults experience greater head acceleration during faster movement and when using a compensatory step response after a balance perturbation. In both cases, it appears that the capacity to absorb energy diminishes with age, so the energy at the foot is propagated up the system, leading to increased head acceleration. The occurrence of tripping and falling is on the rise among our elderly population. In spite of research into the area, the occurrence of hip fractures is on the rise in the elderly population, as are fall related injuries. Of particular concern are side falls which increase the likelihood of fracture by as much as six to twenty times the norm. Frequent falls also increase the likelihood of a side fall substantially increasing the risk of hip fracture. Hip fractures carry a significant economic burden and contribute substantially to increased mortality rate [39]. The increasing cost to insurance companies and governments of paying medical bills for their elderly due to hip fractures highlights the value of further research into this area. Figure 1.7 shows the difference in reactions to tilting along the sagittal plane.

It was observed that the elderly had an inherent resistance to tilting in the trunk area to compensate for lateral tilting [40]. This stiffness was seen to have increased the inherent instability of the elderly. It also appeared to be linked to the change in method of maintaining balance that was employed by the elderly as opposed to their younger counterparts. Understanding why these changes take place could lead to improved balance in the elderly population. The balance board could be used with the elderly for the purposes of testing for the likelihood of a lateral fall.

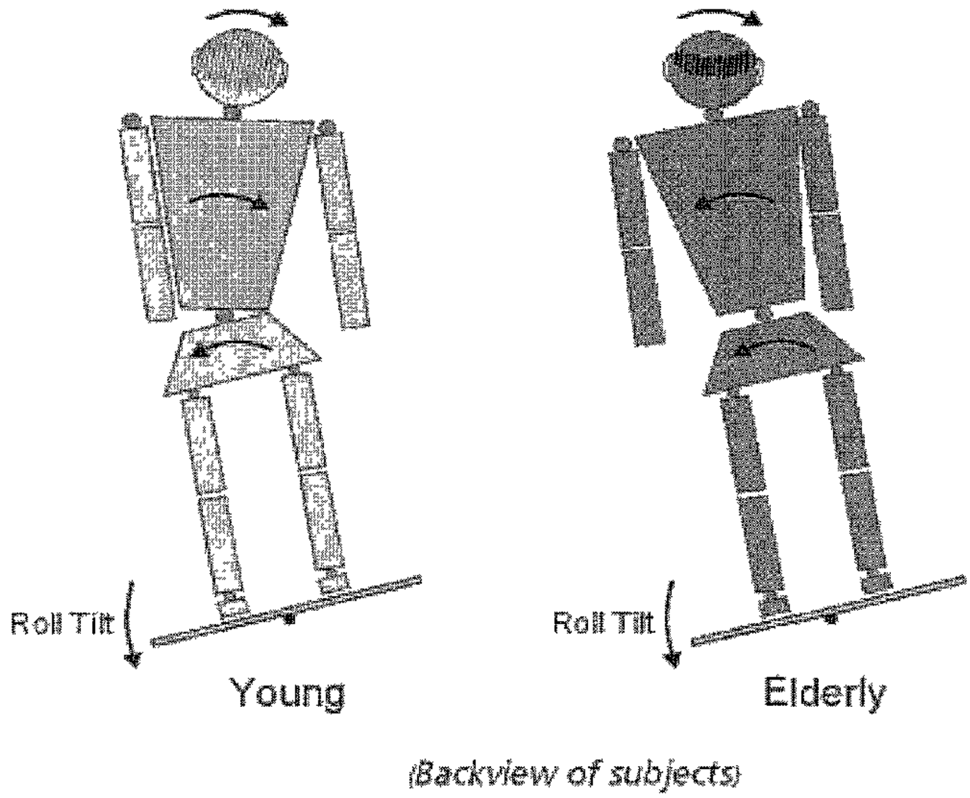

Figure 1.7 Age varying reactions to balance changes [41].

Balance testing was used to evaluate a group of stroke victims in another study [42]. The stroke victims were assessed in this study on a weekly basis for a year. Significant progress was seen as a result of the balance training and was considered to be over and above progress due to familiarisation with the test procedure. It was found that while it was valuable in identifying changes in a group of patients it was less useful in evaluating individual improvements.

Dystonia sufferers have also been shown to be affected by balance related issues [43]. In a recent study it was shown that dystonia could be detected through the use of balance testing as sufferers of phasic cervical dystonia can have an impaired dynamic equilibrium which will show up as a disruption of vestibular input due to repetitive, involuntary head oscillations. For their study, the dynamic portion of the testing was implemented by having the test subject stand on a stabilometer which required the subject to continually adjust their posture to maintain an upright position while on its unstable surface.

Balance board systems can be used to aid people in dealing with Parkinson's disease [44 - 47]. In this recent study 14 patients were involved in balance training twice a day for 14 days. After this training period it was observed that their compensatory step had lengthened and the time to initiate this step decreased. This in effect indicated that they had become more mobile. In a qualitative analysis the test subjects also stated that they felt their quality of life had improved. Furthermore these effects remained for an additional two months without further training. From this it was concluded that this was an effective method of treating Parkinson's. In all of the cases presented in their work, reactive balance was being tested rather than proactive balance. Reactive balance is the balance system that was studied in this thesis, see Chapter Four.

1.3.2 Balance as a predictor of injury

Various studies have been conducted to determine the most frequent injury sites in the human body [48 - 50]. They have shown that the lower extremities consistently sustain more injury and the ankle joint has been shown to be one of the main sites for injury. Another study was conducted by Trojian et. al. to determine whether or not the single leg balance test could be used to determine the level of risk for a subject to incur an ankle related injury [51]. The single leg balance test performed was similar to the Romberg test described in section 1.2.2. A positive association with a failed single leg balance test and ankle injury was found. This indicated that this test could be used to predict the level of risk of an ankle injury in a test subject.

1.3.3 Balance based exercises as rehab and a means to reduce injury

Another purpose of these devices is to mimic real life situations to help the subject to develop muscle strength, speed and co-ordination in specific areas. A new concept in sports training and physiotherapy contends that to enhance abilities for a specific activity the motions to be undertaken should be mimicked as closely as possible in exercise. Training for these real life situations helps to recruit more muscle spindles for improved neuromuscular control and muscle activation in these situations. In time the body rebuilds the fibers necessary for these motions so that the next time they encounter that situation the body is prepared to handle it. Each time the body is taken a little further beyond what it was capable of before and each time it rebuilds itself to a level where it would be capable of handling the previous situation. This process continues with the body adapting to each new overload until the desired level is reached.

Balance board training and balance training in general has been shown to vastly reduce the occurrence of re-injury in subjects with an ankle injury or reduce the chance of a first time injury [52 - 56]. In this study, a group of 144 subjects, 65 of which had a previous ankle injury, were given balance board training to improve their balance they then showed a statistically significant improvement for re-injury as compared with those who had not received any balance training.

1.4 Other balance board system designs

This section looks at some of the other balance platforms available commercially or for research projects. A comparison with the balance platform developed for this thesis is also presented.

1.4.1 Equipment used in assessing balance

Various types of equipment have been used in balance testing and training some of the common examples are balance boards, swiss balls, soft foam mats and other variations on these products. They all work on the principle of providing an unstable surface for the user to attempt to maintain their balance upon. The balance platform developed for this thesis will be compared with three other systems detailed below.

1.4.2 Commercial products

The Biodex Stability System is one of the commercially available balance assessment products [57, 58]. It provides a 20° range of motion tilting in 360° and interfaces with Biodex version 3.1, software to measure the balance of the test subject. It creates tilting motion by allowing controlled instability to occur. It does not actively tilt the surface on which the user stands but allows the user to adjust the level of instability of the top plate so that any unbalanced movements by the test subject cause the board to tilt in the direction of the movement. This tests the subject's ability to maintain balance rather than their ability to react to an unexpected disturbance. Features of this system are listed below [59].

- High Resolution Color Touch-Screen LCD Display - easy to see and use
- Visual Biofeedback - real-time biofeedback prompts patients into proper postural and balance control
- Five Training Modes and Four Protocols - for versatility
- Interactive Game-Like Balance Training - increases patient interaction and compliance
- Standardized Fall Screening and Athlete Knee Injury Screening Tests - simple, quick and accurate. Test results are compared to age- and gender-dependent normative data to help identify fall candidates and athletes predisposed to knee injury.
- Twelve Levels of Platform Control as well as Static Force settings - allows testing, training and rehabilitation programs for diverse populations
- Balance Training includes - proprioception and stabilization exercise, range of motion and weight shift exercises
- Objective Documentation - printed color reports track progress and document outcomes - ideal for insurance reimbursement
- Data Storage - store more than 1000 tests for later recall or data export
- Data Export - serial interface allows download of patient data to computer for archiving, reporting or export as a CSV file
- Locking Surface - ensures safe "on and off" patient movement
- Adjustable Support Handle - locks in place for safety or swings away for an unobstructed open environment allowing a variety of training activities
- Mobility - transport wheels allow easy relocation between the clinic and community-based fall screening programs and health fairs

Figures 1.8 (a) and (b) both show the Biodex balance system in use. The top plate tilting surface can be identified as the grey circular disc on which the test subjects are standing.

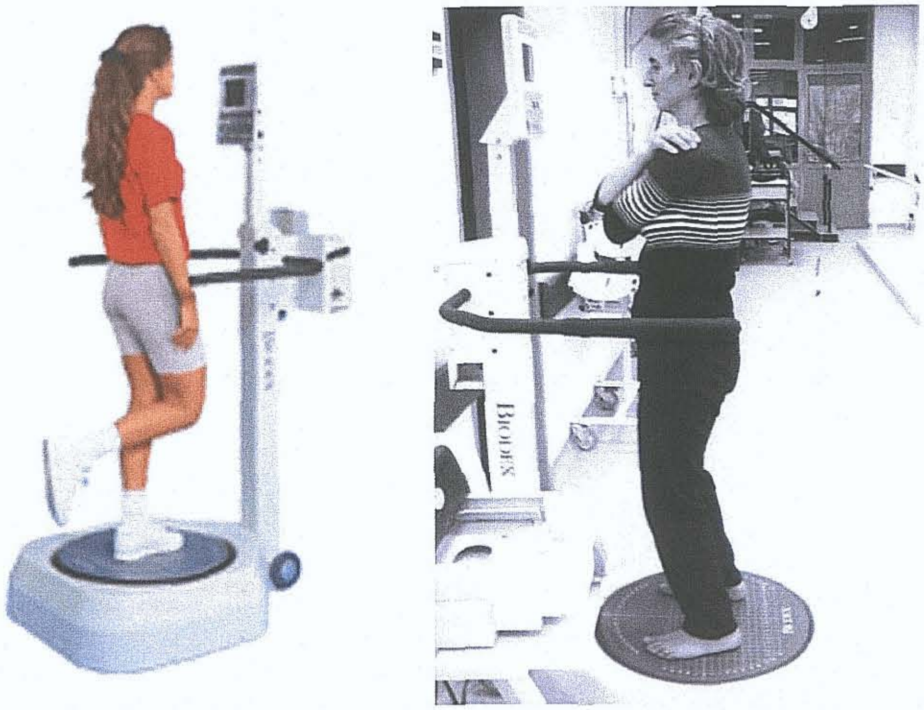

Figure 1.8 Biodex balance platform being used in a Romberg test
(a) one legged stance [60] and (b) two legged quiescent stance [61].

Arnold and Schmitz used the Biodex Stability System (Biodex Inc, NY) to assess the anteroposterior (A/P) component of postural sway. From this work they noted that A/P is very closely related to and accounts for 95% of the overall postural sway [62].

Another balance system is shown in Figure 1.9. This is the Balance Master (BM15) and was used by the National Service Framework for Older People to examine the effect of regular training over a four week period with this device on lower limb muscle strength, explosive power, static and dynamic balance, balance confidence and functional ability in a group of community dwelling people aged 65 and over [63]. This was done to determine it's effectiveness in providing a safe means for the elderly to improve their balance without the need to see a specialist therapist. If this could be achieved it could be used in regular training to reduce the likelihood of falling.

It was found in this study that the BM15 greatly improved lower limb strength in the patients. Also it was perceived to be a very accessible training tool as they 'only have to stand', 'they can hold on' if they need to and 'the machine does the work'. This breaks down the perceived barriers to improved balance and quality of life in the elderly.

The BM15 allowed for variance of the speeds and angles used. The angles described in this study were 5, 10 and 15 degrees. It also allowed for predetermined speed settings with levels from 1-6 mentioned in this report.

Figure 1.9 The Balance Master (BMI5) [64]

Figure 1.10 shows another system, the Kinesthetic Ability Trainer 2000 (KAT2000) balance platform in use. In this particular study it was used to assess static one leg balance and dynamic two leg balance. The KAT 2000 has a central pivot to move about in a 360 range of motion [65]. Underneath this is a series of air bladders, the pressure in these is varied to adjust the level of instability in the platform. When fully inflated the platform can provide a stable surface for the test subject to stand upon when in a dynamic testing situation the bladders can be depressurised somewhat to allow a level of instability. The test subject then has to attempt to keep the platform in a stable horizontal alignment. A tilt sensor registers the angle of the platform 18.2 times per second during testing and allows the tester to determine the level of balance the test subject is able to maintain. This measurement along with two others is used to generate a BI (Balance Index) score. This score quantifies the test subject's ability to maintain the level position. The lower the BI score the higher the level of balance. Feedback is provided to the subject via a computer screen which shows a cursor to indicate their current level of balance. The test subject is tasked with keeping this cursor over an on screen crosshair, doing this indicates they are maintaining balance.

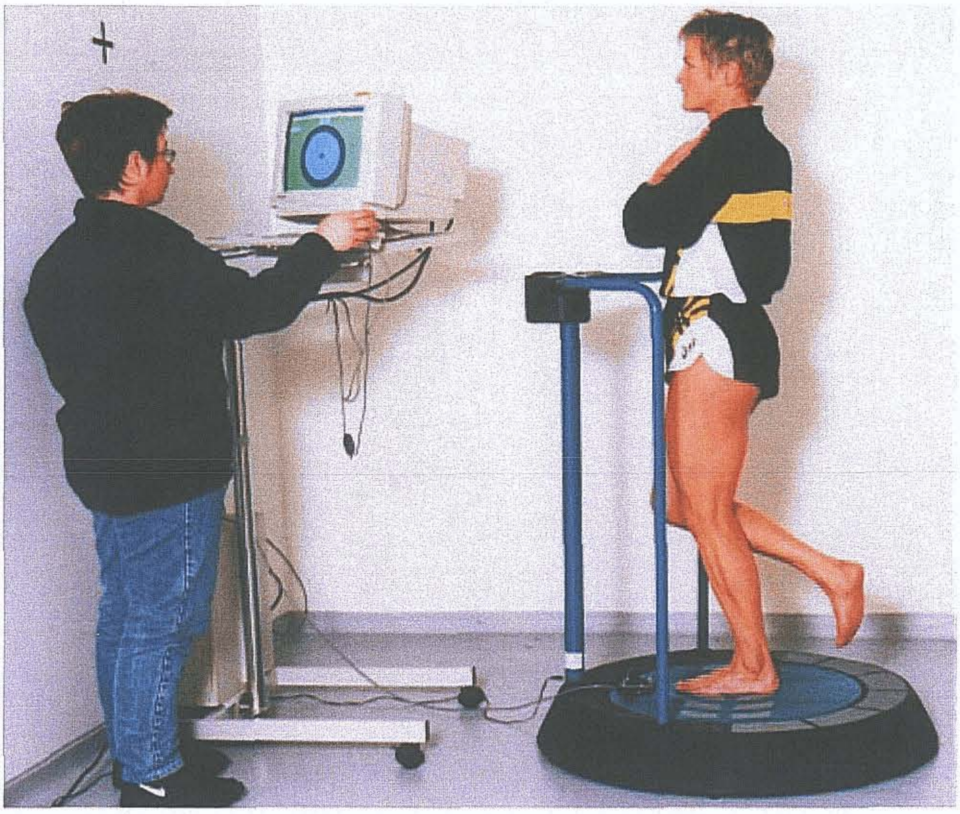

Figure 1.10 The KAT 2000 balance platform [66].

1.4.3 Usefulness of the system developed in this work

Tests can be performed with the developed system to assess the people's reaction to a dynamic situation. Previously in the Romberg test the subject was tested within a static environment. While useful for assessment of balance while motionless, (proprioception, or rather their ability to maintain stability with only small correctional muscular contractions), it did not realistically assess how the subject reacted to a real world environment. The system developed in this project provides the tester with the ability to apply changes and assess the subject's dynamic response to unexpected changes in their environment. It allows assessment of the responsiveness of the subject's reactive system, the response latencies of the muscles, as well as testing their proactive system.

This project also allows the testing of balance instead of only testing the subject's ability to maintain a particular stance for a predetermined time and comparing these to the population norm. Balance can be tested with irregular perturbances or even without motor control with the system in unconstrained (free) operation. These perturbances and their uses were mentioned in the previous paragraph. The testing in free mode is similar to postural stability exercises on balance boards. These exercises were used to develop the stabiliser muscles used in maintaining balance. These smaller muscle groups are used to make minor adjustments to the subject's posture and in so doing maintain balance. This form of testing has been used by one of the Premier League soccer clubs in Germany to screen potential players for possibility of ankle injuries. The test involves standing on the unstable surface for 60 seconds, those who are more likely to have ankle injuries tend to fail at the 45 second mark on average. This test quite simply assesses the strength and neuromuscular control of the stabiliser musculotendonar system in the ankle and its ability to produce a correcting torque rapidly in response to prompting from the body's posture maintaining control systems, i.e. somatosensory, vestibular or visual.

Reaction speed can be assessed by measuring how long the subject takes to regain a balanced posture after a perturbance has been applied to disrupt their centre of balance. This can be done by using the tracking marker in the RS Scan display to see how far the subject's centre of balance is disrupted, how long before the representative marker returns to within an accepted deviation from the COP (Centre Of Pressure) and maintains this for at least 5 seconds. The RS Scan software can be set to show a representative marker that gives real time tracking of the subject's centre of pressure.

Previously perturbances were induced mainly by the tester pushing or pulling the subject in the desired direction. The amount of force used was stated as a rough grouping with broad category bands. The exact conditions for these perturbances were impossible to reproduce for each test with any degree of accuracy. This project can reproduce the same level of perturbance for each and every test so long as the subject maintains the same position on the board for the tests. This can easily be done by inscribing foot placement markers on its surface.

One similar system that is commercially available is the Biodex Balance System and this was priced in October of 2002 at €12,000 + VAT for the basic version. Not many other options were commercially available. Most similar systems were once off products built specially for a particular study, and hence were available at premium prices only. The system was designed with the intention of providing a cheaper alternative to commercially available products. One of these was the Biodex Stability System available from Biodex which was quoted more recently as costing €12,071 (quotation from IPRS, distributor for Biodex, 2005), this can be seen in Appendix H.

1.5 Balance platform developed for this thesis

1.5.1 Tests that were performed with the balance board

Outlined in previous sections are the tests for which the balance board can be used. During the experimental work for this thesis, the designed system was to be used for the purposes of subjecting the person on it to a change in their centre of gravity by tilting the Top Plate on which they stood. This would force them to react and adjust to this change in their environment. When used in conjunction with a Force Plate these readings would present a detailed view of the test subject's reactions. This would allow an assessment of how well they would be able to react to unexpected changes in their environment. This tilting motion was initially performed in this work by using electric motors. In the final design, pneumatic actuators were used to tilt the Top Pate. Both of these designs were implemented and characterised. This work is detailed in the following Chapters.

1.5.2 Overview of the balance platform

The purpose of this machine was to test the subject's ability to return their centre of pressure to its normal resting point, while allowing for postural sway. The machine designed in this work was developed to overcome this problem by having the force applied through a controllable consistent mechanical means. Thus a consistent force could be applied to the test subject allowing for greater validity of experimental results. This force was to be applied through the plate on which the subject would be standing. Figure 1.11 indicates the range of motion possible for the top plate.

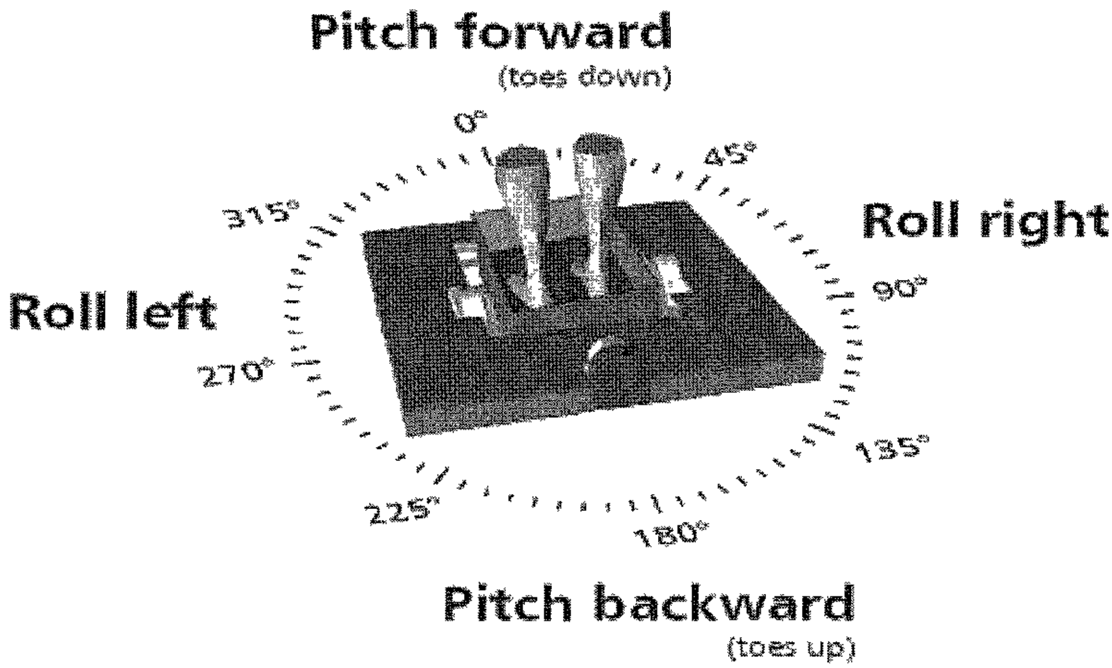

Figure 1.11 Possible tilting motions for balance platform [67].

Pneumatic actuators were aligned one to each edge of the Top Plate situated as far from the centre as possible to take full advantage of leverage effects. These pneumatic cylinders connected to the Top Plate via universal ball and socket type joints. Tilting could be achieved along one axis with the use of two cylinders while the other two remained un-actuated. Tilting along two axes at once could also be accommodated to some degree because the universal joints provide the necessary flexibility. With this level of motion possible the system could be used for more complicated tests requiring a greater degree of balance from the test subject and allow for testing of elite athletes who otherwise might not feel challenged. With the actuators set to continue motion for an extended period of time at a slower rate of tilting, rehabilitation and training can be offered to the test subject standing upon it. This design presented the greatest scope for further investigations.

Chapter 2

Motor Actuated Balance Board

2.1 Motor balance board design

During my final year project in 2002 / 2003 I designed and implemented an initial build of a balance board which was actuated by a motor driven system [68]. While this system worked with low load on the board, it was unable to move the platform when loaded with human equivalent weight due to friction in the system.

The version of the balance board used for the final year project (FYP) was similar to that used for the motorised build developed during the work presented in this thesis with a few important differences, listed below

The aims for the motorised design were

- To increase the size of the top plate
- Use of stronger motors
- PC control of the balance platform
- Implement a braking system for the top plate

The developments on the motor actuated design of the balance board may be summarised as follows:

- Changed from micro switch control to PC control
- Increased size of the top plate.
- Used more powerful motors to allow for greater torque development in board.

Other design issues that were dealt with in this part of the system development were

- The choice of axial joint and its influences on range of motion.
- The number of axes of tilt of the board.
- The materials to be used for the top plate and base plate.
- A safety mechanism to reduce the risk of injury to the test subject.

- Choice of actuators and design of actuating system

Although the Final Year Project was a substantial achievement, it did not realise the full potential of the initial concept. This thesis details the improvements made to produce a useful system.

The design that was implemented during this phase of the work is shown in Figures 2.1 and 2.2. The reference frame for the top plate movement is shown in Figure 2.2 and the naming convention used for the individual components is shown in Figure 2.1. The controlling program was developed in LabView. A Graphical User Interface with a switch to allow the system user to select whether the board was tilted to the left or right was developed with this software. When the switch was toggled to either the left or right a series of eight relays was triggered to allow the electricity from the PSU (power supply unit) to flow with the correct polarity to the DC motors. This determined the tilting direction of the top plate. This design did not allow for a neutral position to be maintained. Design requirements for the new system included that it should be capable of tilting the top plate over and back within one second to provide the person with sufficient perturbation. The implemented system was also to be capable of a +/- 15° total range of motion.

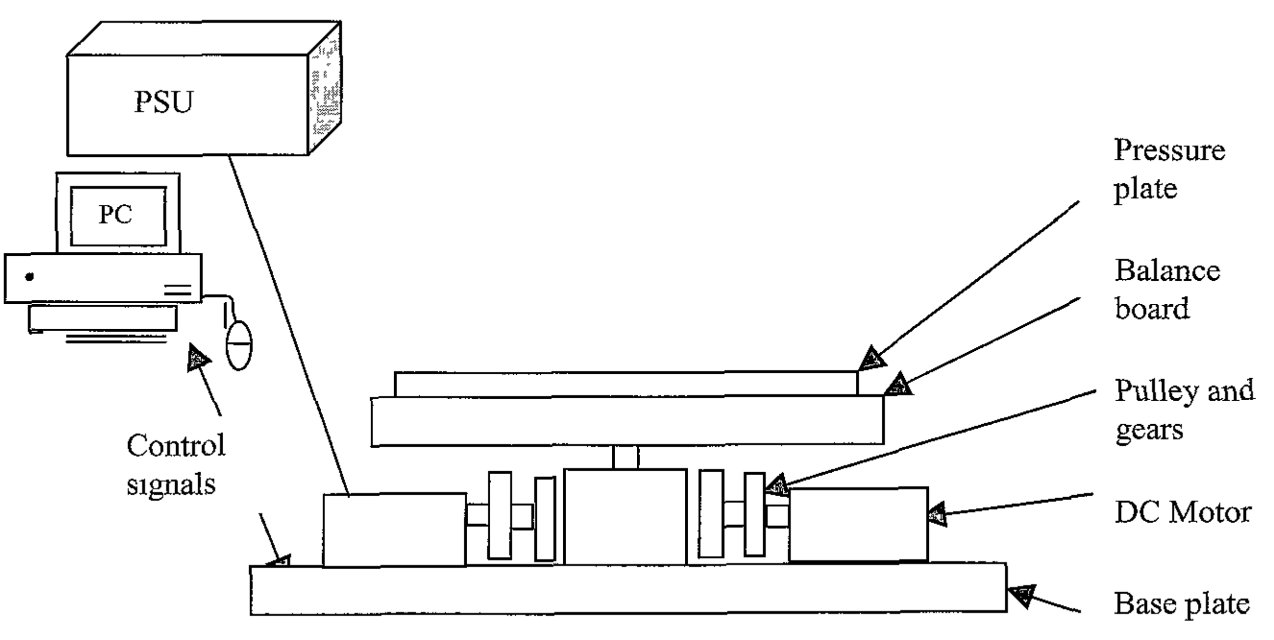

Figure 2.1 The design implemented for the PC motor controlled balance board.

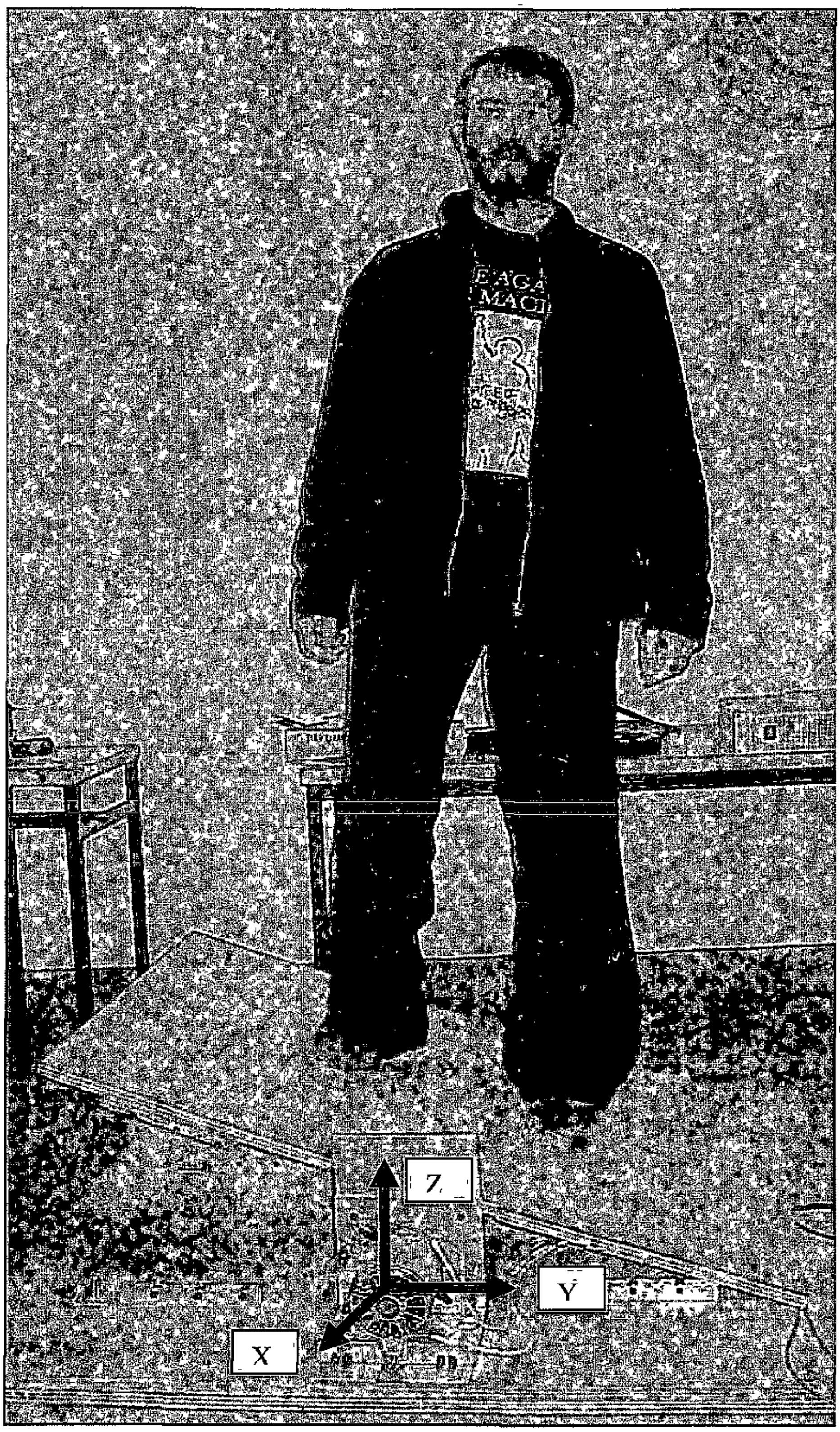

Figure 2.2 Motorised actuation of balance board (pressure plate not shown)

2.1.1 Top Plate, Base Plate and Universal Bearing Joint

In the design of this system one of the first issues was the material choice for the top and base plate. Marine plywood, ¾ inches thick was chosen for its rigidity, strength, relatively low cost and lower weight compared to the other materials considered e.g., aluminium and steel. It was acquired in standard sized sheets of 2.4m x 1.2m (8' x 4') at €31.41 per sheet. The aluminium and steel were priced much higher. The largest standard sized plate of aluminium was 0.5m x 0.5m from suppliers Miko Metals. Larger sizes were obtainable at premium prices. Table 2.1 shows some of the other materials considered for the top and base plates. The universal joint, shown in figure 2.3, allowed tilting about all three axes. This joint was a component in the steering transmission for the Opel Corsa (2003 model) car and is typically found next to the wheel where large loadings can occur. It was found by experimentation that this component could easily carry the applied loading for this work. The range of motion provided by this was +/- 18.8°. This was measured using a high speed camera and UTHSCSA *ImageTool* program (developed at the University of Texas Health Science Center at San Antonio, Texas and available from the Internet by anonymous FTP from maxrad6.uthscsa.edu). The measurement of these angles is described in detail in section 3.2.3.

Material	**Young's Modulus**	**Shear Modulus**	**Density**	**Tensile Strength**	**Proof Stress**
	E	**G**	ρ	σ_T	σ_y
	GN/m2	**GN/m2**	**kg/m3**	**GN/m2**	**MN/m2**
Stainless Steel	196	87	7950	1295	1120
Mild Steel	207	81	7850	462	280
Aluminum	72	27	2626	320 - 550	250 - 450
Douglas Fir	14		545	125	56
Red Oak	12.5			132	59
Plywood*	12.4				

Table 2.1 Material properties considered for selection of top and base plates [69], [71]

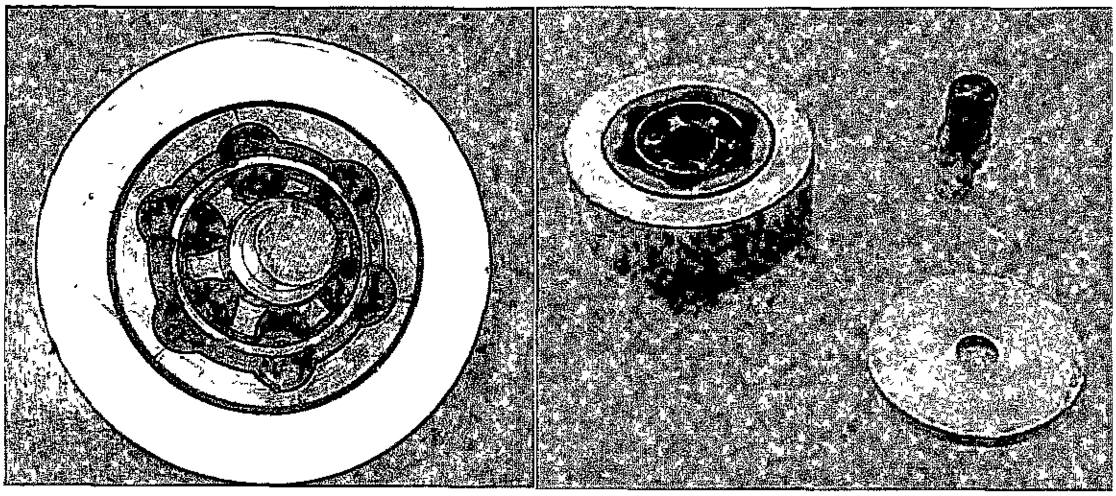

Figure 2.3 Universal Bearing Joint used centrally under the balance board

2.1.2 Motors and Relay System

Large DC and AC electric motors could have provided the necessary torque for the system and would also have been capable of moving the Top Plate at the required speeds. AC motors being the workhorses of industry would have been cheaper to purchase in the required power/torque rating. DC motors allowed for easier control and the torque requirements were able to be met with available DC motors. The type of controller required for the AC motors increased the price of this option to that of a DC system. ABB and Torsion Dynamics were two of the suppliers contacted for quotations for these motors. The lowest quote for the motor option was in excess of €2,500. DC and AC motors systems required an electro motor brake and gearing system to translate the rotational motion of the motors into linear motion. Stepper motors were also considered and dismissed on cost vs. power output and speed rationale. Calculations used to specify the motor requirements for this are shown in section 2.2.1.

Two DC motors were used to control the movement of the top plate. The motors were controlled by adjusting the input and direction of the power across them to cause the motors to spin clockwise or counterclockwise as desired. The motors were arranged facing one another so they were spun in opposite directions to cause tilting. This arrangement is shown in figure 2.5. The various parts referred to by numbers in figure 2.4 were as follows.

1 – Pulleys

2 – Electric motors (Vickers Polymotor 1Nm DC motor)

3 – Universal bearing joint

4 – Relay based control circuit

5 – Cable reel

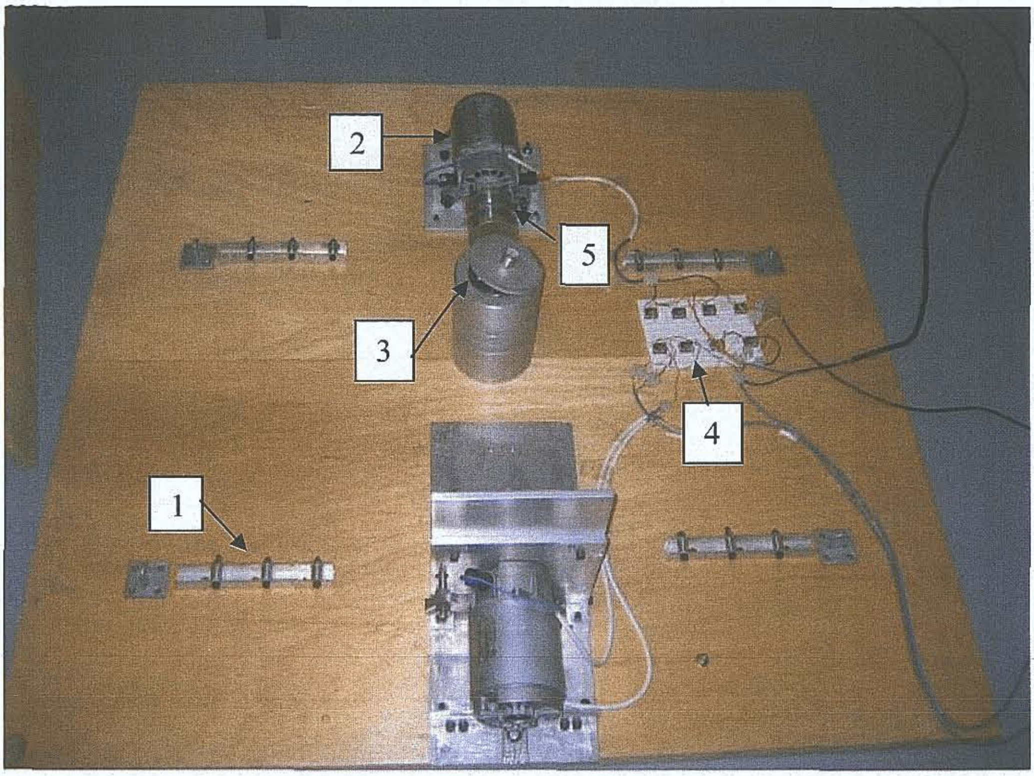

Figure 2.4 Motorised design actuator setup

A control program was developed to allow the user to select the direction the top plate would tilt. On the basis of the selected direction, output signals were sent via a LabVIEW PCI DAQ (data acquisition and control card) to the relay based control circuit. These relays controlled the power going to the motors from the power supply. They dictated the direction in which the power flowed across the terminals of the motors and also whether any power was flowing to the motors. A schematic of this control algorithm is shown in figure 2.5. Tilting to the left and to the right could be achieved by running the motors in opposite directions. Braking could be achieved by running the motors in the same direction. There was also a neutral condition in which the motors were un-activated. This level of control required four relays per motor. The middle condition of braking where the motors were run against one another was detrimental to their lifespan. The relay setup is described in more detail below and depicted further in figure 2.6 and 2.7.

Figure 2.6 shows the relay based control circuit diagram. The eight 5V digital control signals were controlled via the LabVIEW PCI DAQ card.

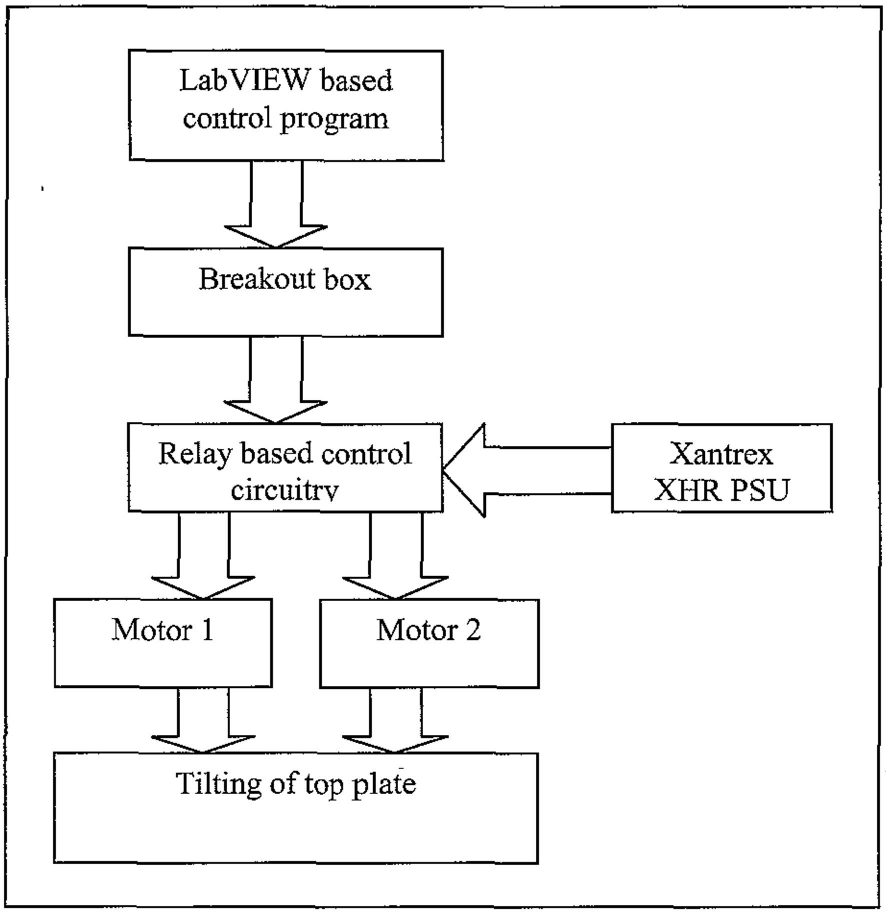

Figure 2.5 Overview of motor based control system

Relays 0-3 are represented by the lower row of relays in Figure 2.7 going from right to left. Please note that Relay 0 and Relay 1 were connected to the positive terminal of the Xantrex power supply and Relay 2 and Relay 3 were connected to the negative terminal of the same power supply. The positive and negative from the XHR PSU was fed into 2 of the relays per motor.

Four digital outputs from the PC were connected across the switching terminals of Relays 0-3 respectively, thus allowing them to be directly controlled through LabVIEW. For one of the motors to be switched on, two of the relays had to be activated. For motion in one direction, Relay 0 and Relay 2 were bridged while for motion in the other direction Relay 1 and Relay 3 were bridged. Four relays were used instead of two because this allowed an off state to be created as well as giving directional control. Creating the bridge between the relevant relays completed the circuit and allowed tilting of the plate.

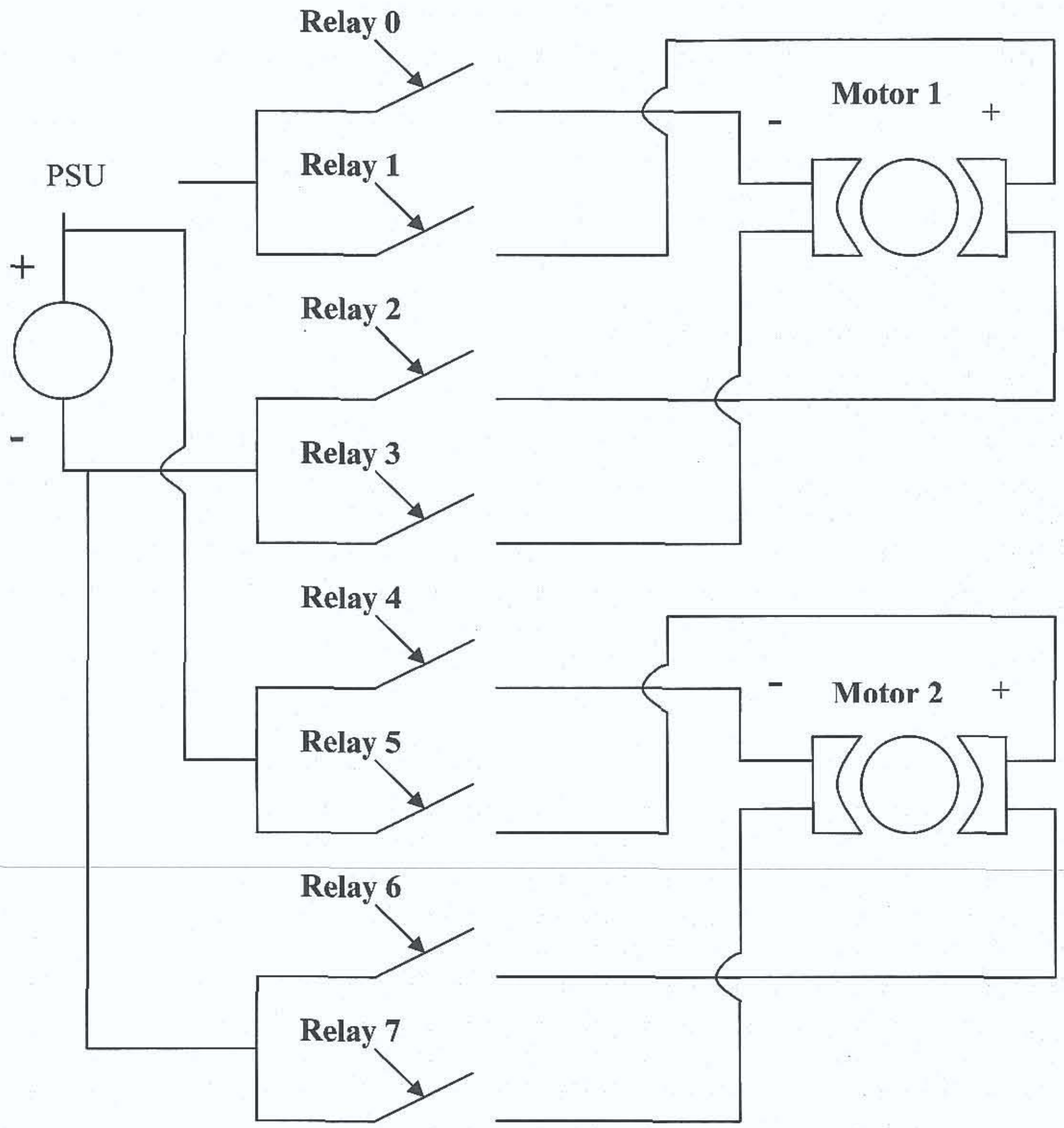

Figure 2.6 Circuit diagram for motorised design control circuit

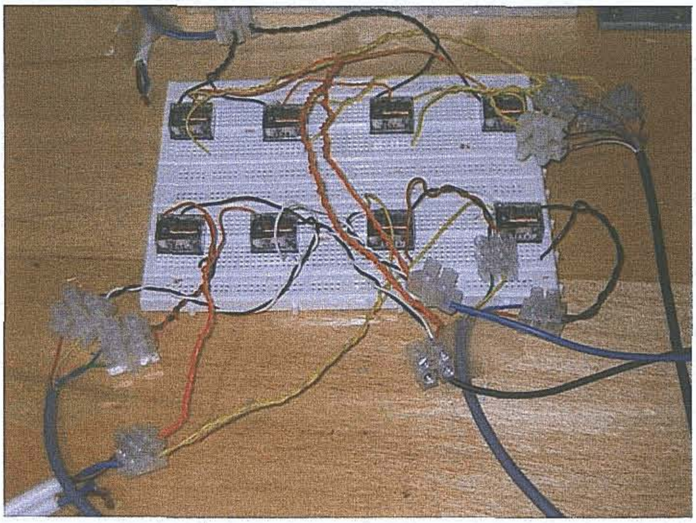

Figure 2.7 Relay control circuitry

Table 2.2 shows the logic table for the relay control circuit used in this design. This table indicates which relays need to be triggered to control the motors.

	Relay 0	Relay 1	Relay 2	Relay 3
Relay 0	0	0	1	0
Relay 1	0	0	0	1
Relay 2	1	0	0	0
Relay 3	0	1	0	0

Table 2.2 Logic table for relay control circuit

2.1.3 Pulleys and Pulley Cables

Nylon coated steel was chosen as the pulley cord material. This had a rated breaking strength of 1,334 N. From each motor two lines ran, one to each side of the board giving a maximum loading of 2668N. This allowed both motors to pull the board regardless of the direction of tilting and afforded maximal efficiency. . This exceeded the maximum allowed weight for a test subject for the top plate, 100kg, plus the weight of the top plate, 35kg. All four pulley cables needed to be kept under tension at all times to give a smooth pulling motion. Any slack in the cable produced a jerky motion upon changing direction. This need for tension in the cable meant that there could only be one axis of tilting motion. To create a second axis would have required two additional motors being mounted the top plate. The pulleys used can be seen in figures 2.1 and 2.4.

2.1.4 PC Control Hardware and Software

A LabVIEW based control program was developed to control the motion of the top plate. This included a switch to select direction and a safety on/off switch within the program. The GUI for this program is shown in Figure 2.8. A PCI based LabVIEW card was used and this allowed for the eight digital outputs needed to be sent to the relay control circuit via the LabVIEW breakout box shown in Figure 2.9. The digital outputs 0-7 on the LabVIEW breakout box were used to control the states of the relay control circuitry which was used to alter the direction and on or off state of the motors that were used to drive the balance board.

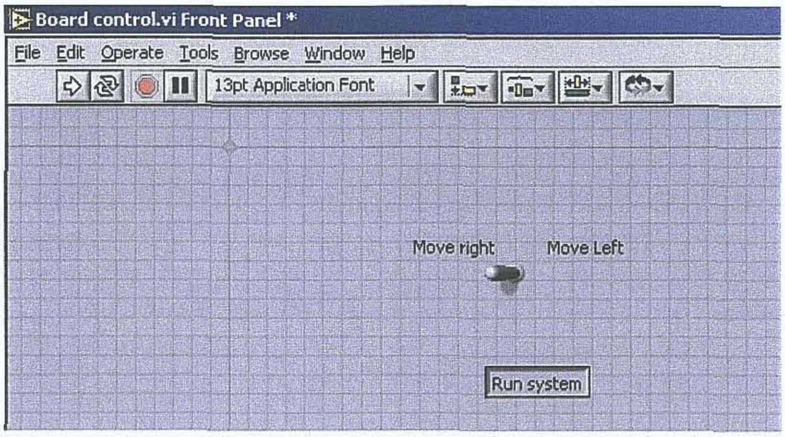

Figure 2.8 Control panel for motorised build

Digital outputs 0-3 were assigned to motor 1 and outputs 4-7 were assigned to motor 2. Each of these outputs were connected to only one relay, the relays were then used in pairs to control direction on the motors. These were not controlled via timer but responded to a manual switch, which controlled the left and right tilting of the board. This also had a second switch to shut down the entire system once the test was finished. The toggle switches for left or right tilting of the board were disabled until the 'run system' switch was activated. Hence there would be no motion until the power "on" switch was activated within the LabVIEW developed GUI, giving an extra layer of safety and protection for the test subject. The two states for the block diagram of this program are shown in Figures 2.10 and 2.11.

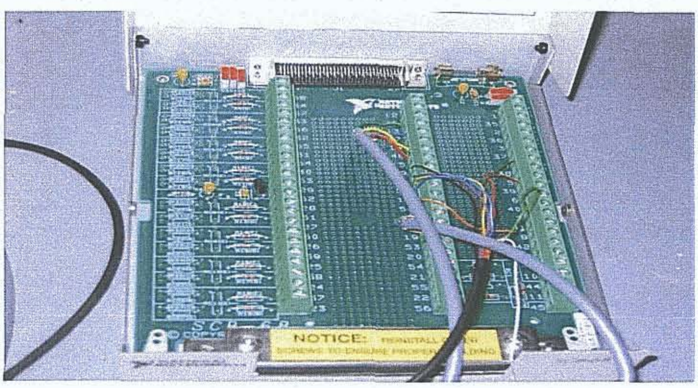

Figure 2.9 LabVIEW breakout box

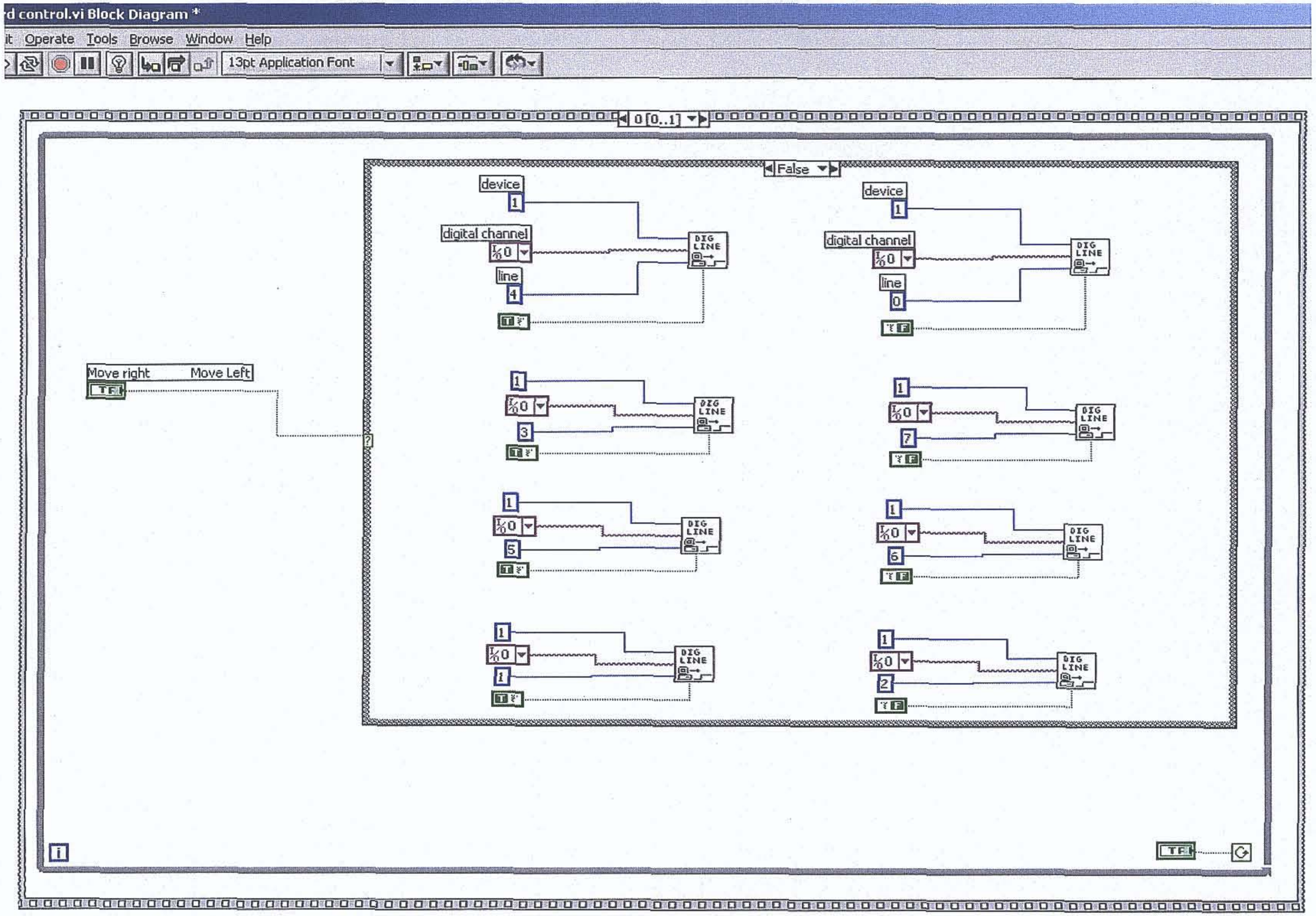

Figure 2.10 Control program for motorised build tilting to the right

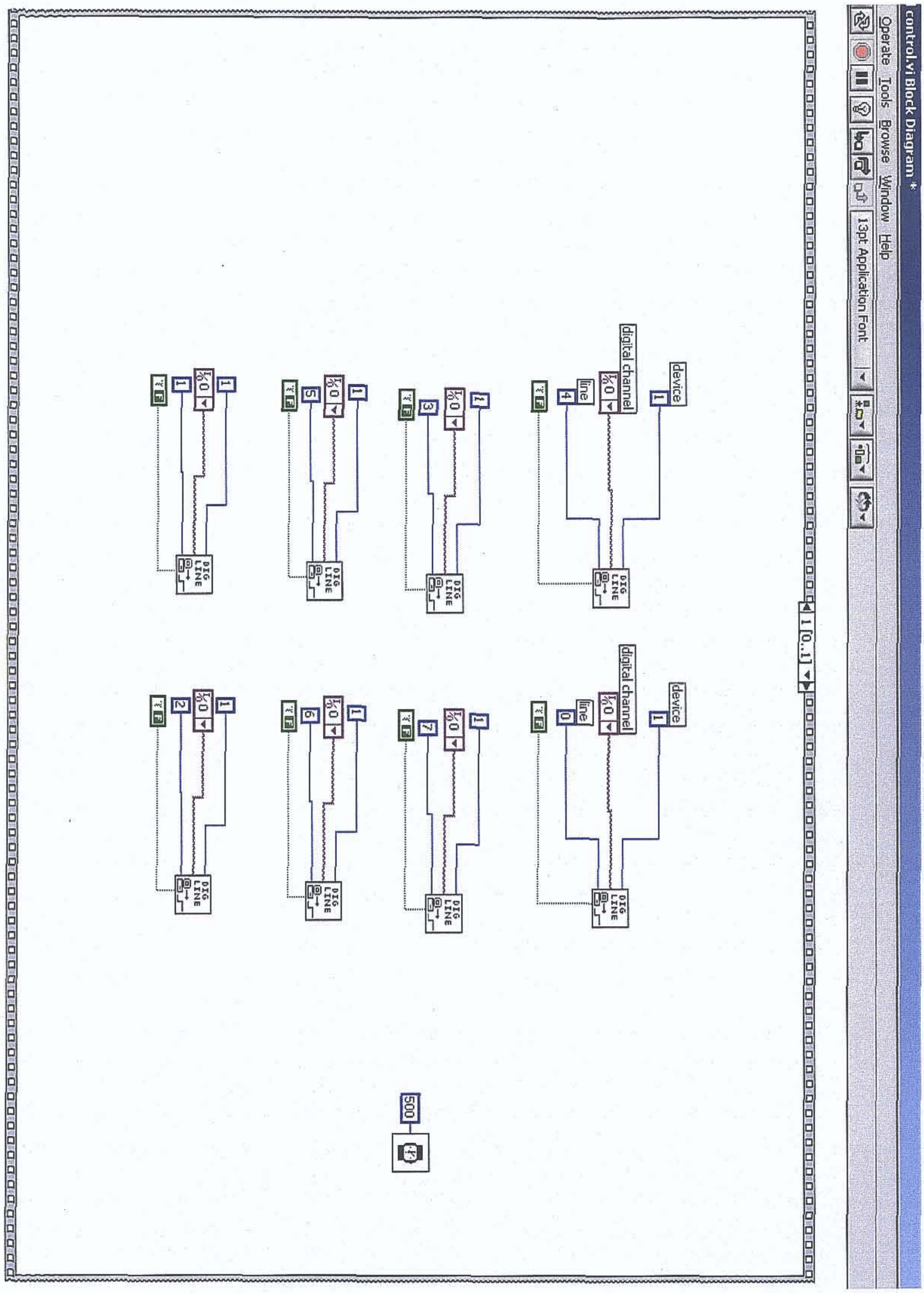

Figure 2.11 Control program for motorised build neutral starting position

2 Analysis of motor design

2.2.1 Mechanics of the top plate

Moment generated by motor – Theory

Knowing the moment generated by the motor allowed determination of the turning force applied to the top plate and the selection of a suitable motor. The torque rating for the motor used was 1 Nm (T_1). The radius of the motor pulley shaft around which the pulley cable was wound was 0.015m (r_1). The mechanical advantage, k, from pulleys was 12 as 12 cord lengths were connected between the top plate and base plate via 12 pulleys as shown in figure 2.12. This arrangement was also repeated on the opposite side of the plates.

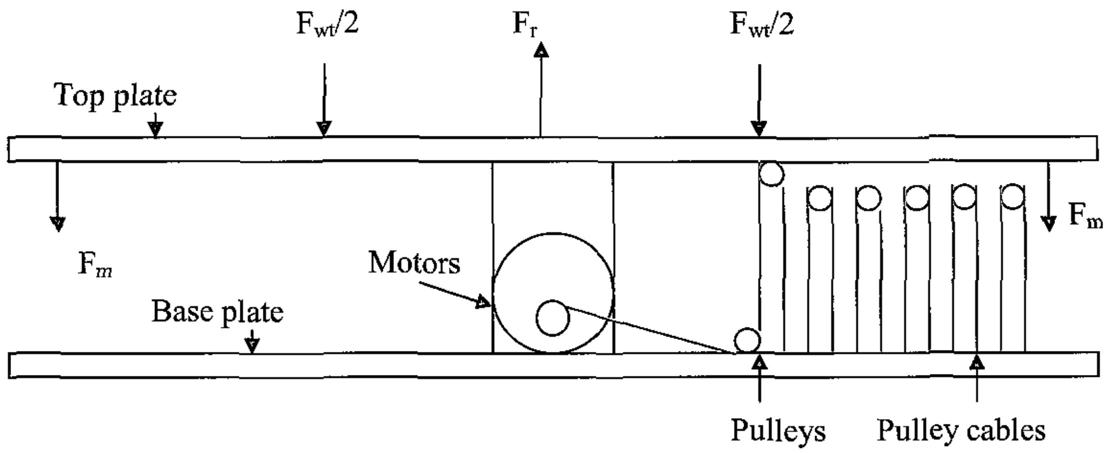

Figure 2.12 Forces acting on motorised design

F_c – Force generated by one motor in cord

T_1 – Torque rating of motor

r_1 – Radius of motor shaft

k – Mechanical advantage from using twelve pulleys attached to each side of a motor

$$F_c = \frac{T_1}{r_1} = \frac{1}{0.015} = 66.66N \quad (2.5)$$

The two motors were wired so that they rotated in opposite directions in order to rotate the board in a specific direction. Therefore, with the two motors pulling in conjunction a force of 133.32 N was applied to two separate cords and through two sets of pulleys to rotate the board. For each pulley set, the first pulley was attached 150mm from the centre and the others were each spaced 50mm thereafter, see figure 2.12. This would provide a torque of 438.4 Nm, as shown in equation 2.6. This analysis assumes the two cord lengths going from one pulley are at the same distance from the fulcrum.

$$T_m = 2*(2F_c*0.15)+(2F_c*0.2)+(2F_c*0.25)+(2F_c*0.3)+(2F_c*0.35)+(2F_c*0.4)]$$
$$=2*[20.0+26.6+33.33+40.0+46.0+53.3] = 438.4 \ Nm \quad (2.6)$$

In general operation, the volunteer would have their weight distributed with both of there feet equidistant either side of the fulcrum and hence produce a net zero static torque about the fulcrum, T_V. In a worst case scenario, if a volunteer of 100 kg stands on one leg at a distance of 0.25 m from the fulcrum they would create a torque, T_V, of 245.25 Nm as shown in equation 2.7. This represents the furthest point the volunteer can have their foot from the centre and while still standing on the pressure plate. From the above design analysis, this torque is well below that which could theoretically be produced from the motors

$$T_v = 100*9.81*0.25$$
$$T_v = 245.25Nm \quad (2.7)$$

The torque exerted by the motor, Tm, was calculated to be sufficient to tilt the top plate. From these calculations it was decided that these two motors were sufficient to tilt the top plate. However during operation frictional forces in the pulley system proved to be significant. Smoother pulleys, lubricated bearings, metal wire cord and nylon cord were all investigated to overcome this problem. The friction still however proved to be a significant force reducing factor. To provide the maximum pulling force, the number of pulleys that were used had to be reduced to two on each side instead of the intended 12 each side. This made continuous movement of the volunteers difficult. In order to achieve an angle of tilt of 15 degrees the height of the board from the base had to be at least 0.134m as calculated from figure 2.13 and shown in equation 2.8

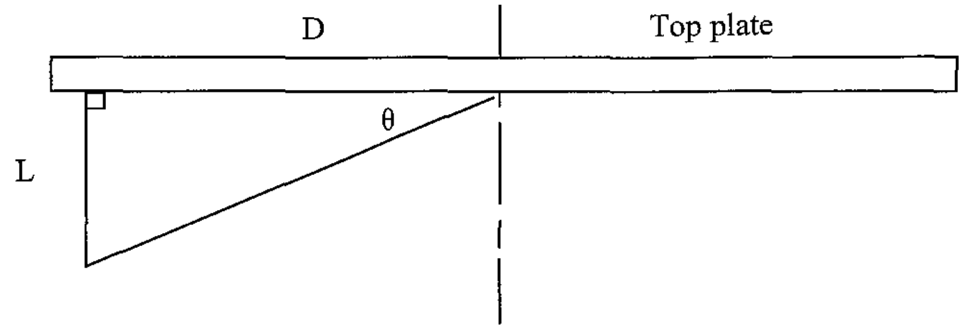

Figure 2.13 Diagram to calculate the top plate range of motion.

$$L = D * Tan\theta = 0.5 * Tan15 = 0.134m \qquad (2.8)$$

Video recordings were made of the motorised balance board being tested with a volunteer standing on top. This volunteer was measured as weighing 61kg and is portrayed in Figure 2.2. The volunteer underwent a series of tiltings that were recorded using a Canon Digital IXUS 500 digital camera at 640x480 resolution and at 30 frames per second. The captured images were measured using UTHSCSA *ImageTool* program (developed at the University of Texas Health Science Center, San Antonio and available freely from the Internet by anonymous FTP from maxrad6.uthscsa.edu). Figures 2.14, 2.15 and 2.16 all show experimentally derived results of system performance. Figure 2.14 shows the angles achieved by the top plate during testing. The curve entitled 'first tilt' in all of these graphs shows the initial movement characteristics of the board after the motion was started from the horizontal position.

As can be seen from the three graphs there is a definite pattern in the results and this relationship is more pronounced in all the graphs once the first tilting motion is discounted. From figure 2.13, each quarter of a cycle took approximately 0.10, 0.25, 0.15, 0.25, 0.05, 0.15, and 0.05 seconds consecutively. These seven quarter cycles represented 1.75 cycles of oscillation and the total time for this motion was 1 second. This indicated that the period of oscillation was approximately 0.57 seconds. The difference in the time for each quarter cycle was due to the jerky nature of the movement in this design. The board did not always move smoothly and due to friction it snagged on occasion which lead to longer periods of oscillation. At the maximum angle of tilt, due to momentum of the system the motor also came to a sudden halt and took some time before moving again. The time taken to reach the horizontal position varied and meant that this build did not achieve a high level of timing repeatability which was one of the design criteria.

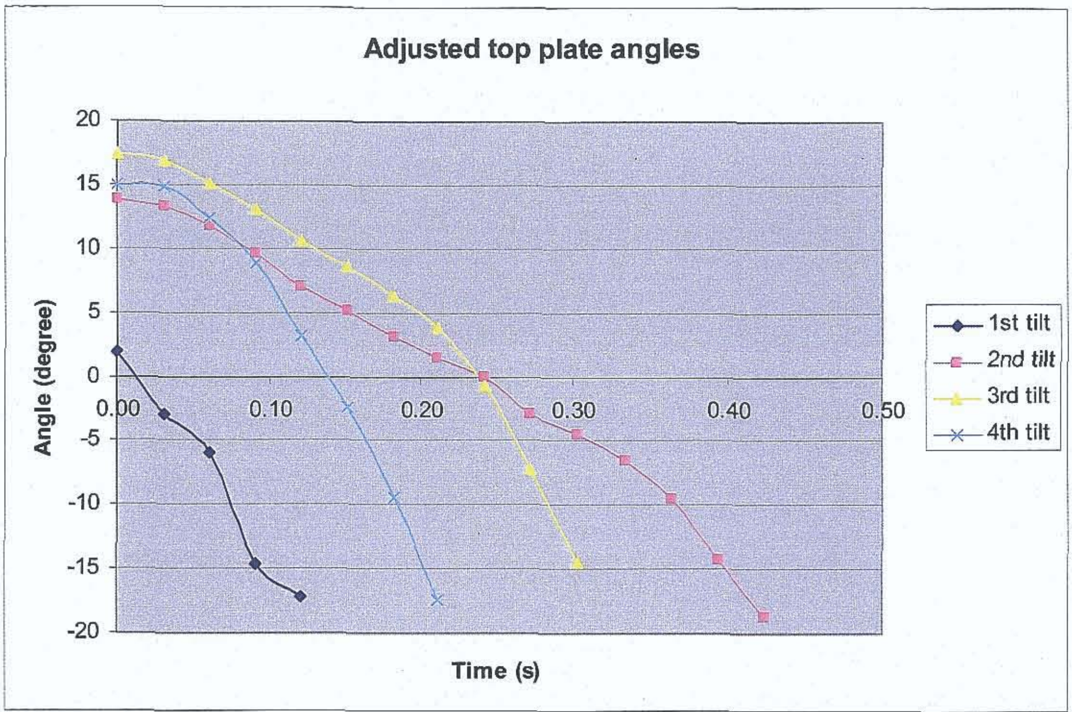

Figure 2.14 Top plate angles achieved experimentally.

Speed capabilities – Theory and Experiments

The mechanical advantage derived from the pulleys, k, was 2.4. ω, the rated speed of the motor used was 10,500rpm for 100V from the specifications plate on the side of the motor. r, was the radius of the reel the pulley cable wrapped around and was measured at 0.015m. V, was the maximum linear velocity at which the pulley cable pulled down the top plate. All information used in these calculations was derived from the plate on the side of the motor, a Vickers Polymotor.

$$V = \frac{\left[\frac{W_1}{60} * 2 * \pi * r\right]}{P} = \frac{\left[\frac{10500}{60} * 2 * 3.14 * 0.015\right]}{2.4} = 6.86 \ m/s \qquad [2.9]$$

The experimental results detailing the velocities achieved by the top plate during testing are shown in figure 2.15. Taking the maximum angular speed of about 280 degrees/s and converting to linear speed with a board radius of 0.5 m, gives 2.44 m/s. This is somewhat lower than the theoretical value and could be accounted for by system losses and also the age and condition of the second hand 20 year old motors. These motors were all that was within the budget for this project at the time.

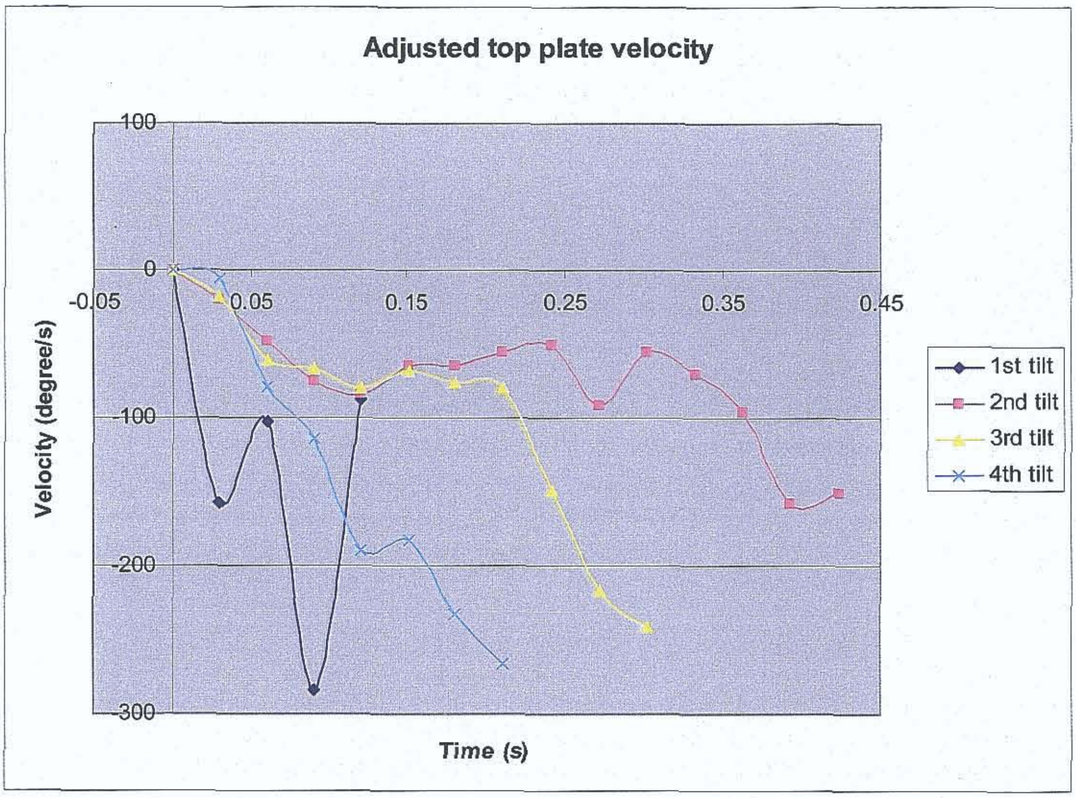

Figure 2.15 Top plate velocities achieved experimentally.

As with the angles recorded there is a definite trend in the results especially once the result from the first tilt are discounted. The results from the first tilt can be discounted when comparing to the other curves as the first tilt was started from a level position and not from a fully tilted position. These results were calculated by differentiating with respect to time the top plate 'angle with time' results shown in figure 2.14.

Acceleration capabilities – Experiments

Figure 2.16 shows the experimental results detailing the accelerations achieved by the top plate during testing.

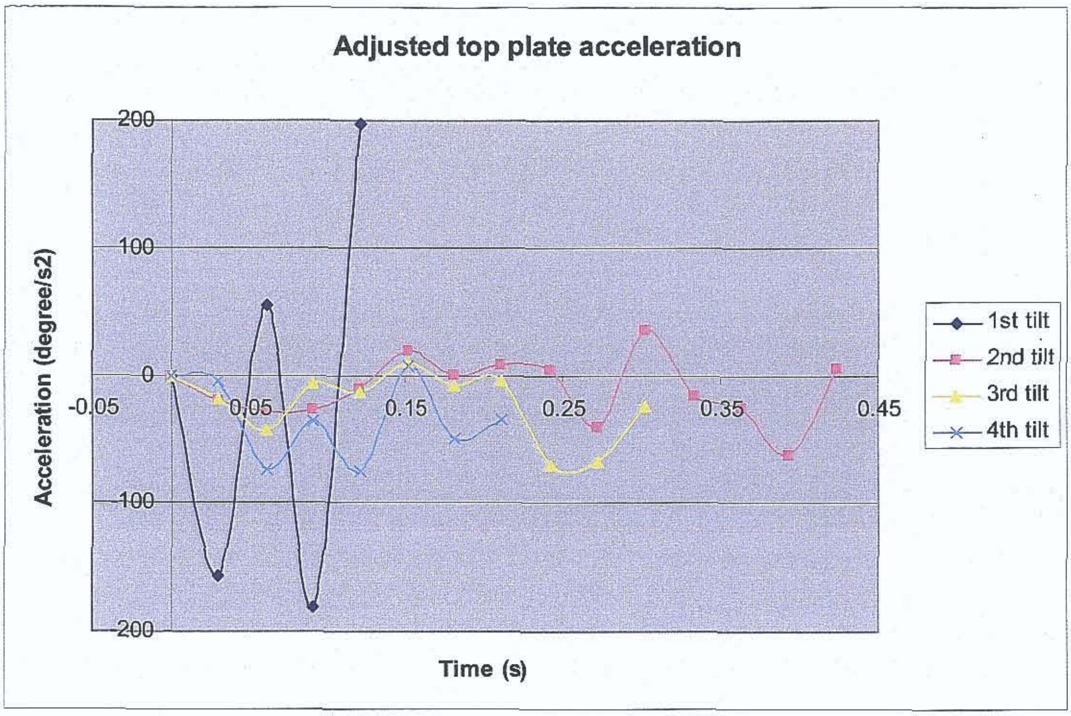

Figure 2.16 Top plate acceleration achieved experimentally.

As can be seen in figure 2.16 the acceleration trends roughly follow one another once the first tilt is discounted. These results were all calculated by differentiating with respect to time the top plate velocities that were recorded and shown in figure 2.15. This shows some repeatability in the design. To improve the repeatability and control of the system, feedback and a controllable electric motor brake could have been used. This however would have been an expensive option with no guarantee of success. This design while being capable of single axis tilting was not considered to be adequate to meet the full needs of this project. This is further discussed in Chapter 5 where a comparison of the two designs (motor and pneumatic actuated) is presented.

Chapter 3

Pneumatic Actuated Balance Board Characterisation

3.1 Pneumatic balance board design

Electro-pneumatically controlled actuators were chosen as a main element of the solution for the new balance system. The sequencing of the valves was controlled via a computer to allow for the first time universal direction tilting of the balance board. A picture of the system is shown in figure 3.1 and a schematic of the system in figure 3.2.

The design goals for this system included:

- The ability to perturb the board to > 15°.
- To be capable of achieving this within 1 second.
- To be capable of multi-axis tilting.
- To be able to interface with and trigger a foot pressure profile monitor.
- To develop a user friendly GUI for this system.
- To be capable of testing with loads of up to 981N (100kg).

Shown in figure 3.1 is the balance platform setup for testing with a volunteer test subject who participated in this part of the study. The test subject was 25 years of age, with no previous history of injuries weighed 81.3kg and was measured at 1.85m in height. Experimental results presented in the rest of this chapter were from tests performed with this individual on the balance board.

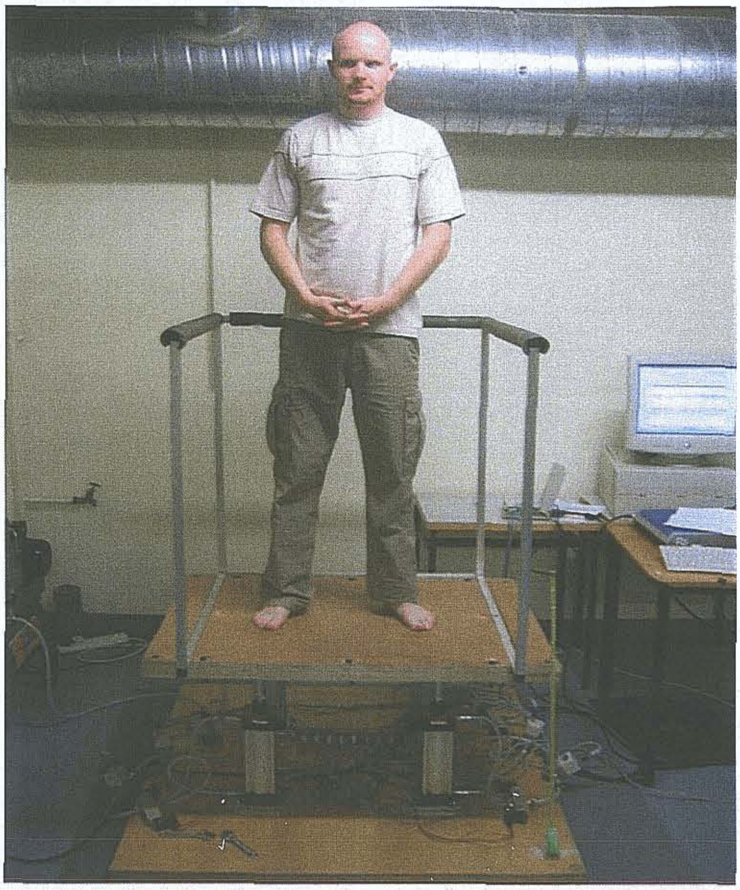

Figure 3.1 Pneumatically actuated balance platform (pressure plate not shown)

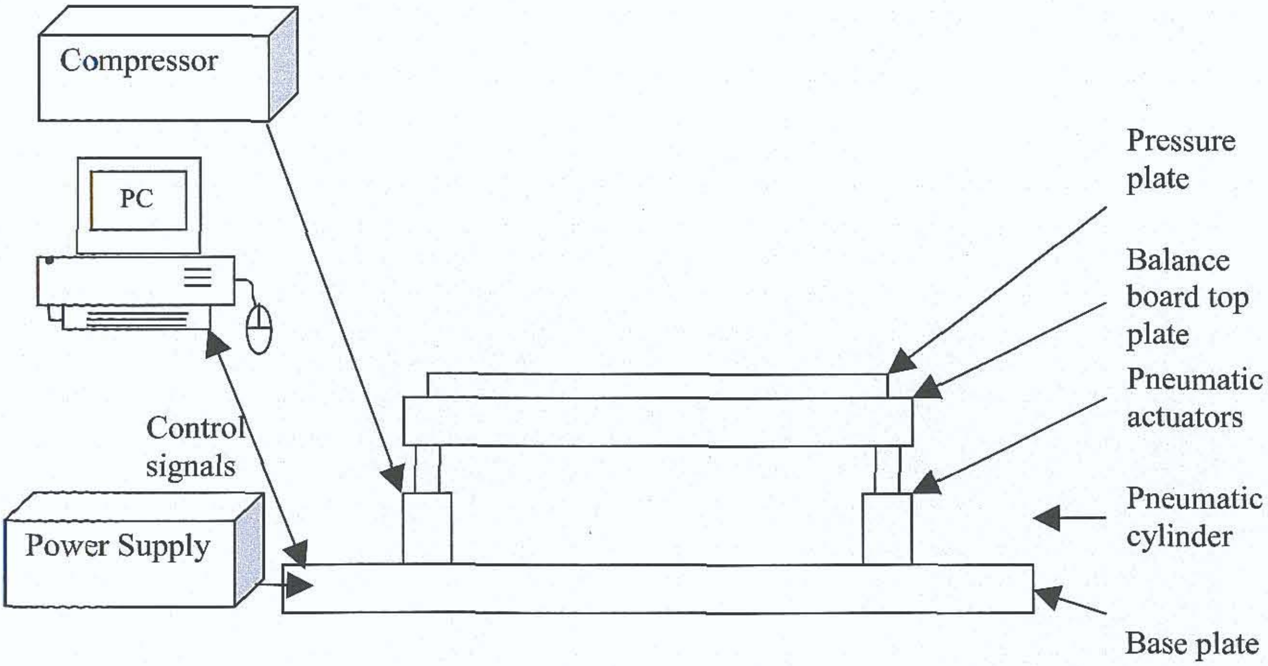

Figure 3.2 Schematic of the pneumatically actuated balance board.

3.1.1 Top plate and base plate

The main criteria for the top and base plate were to provide the person being tested with a firm surface for support that would be able to withstand the forces acting upon them. A foot pressure profile plate was situated on the top plate during operation of the system. As per the initial design analysis, plywood was chosen as the material for the top and base plates.

The base material for the platform was made out of two panels of ¾" thick marine plywood, each measuring 1.2m x 1.2m. These were held together with a layer of adhesive and four bolts. The top plate was made up of two layers of inch thick marine plywood. The pistons were attached to the underside of the top plate. The second top plate plywood sheet covered over the bolt heads where the pistons were located and allowed the safety rail to sit flush with the surface of the top plate. Plywood made a good choice for the base and top plates as it was easily machined to position the flange mountings for the pistons. This meant that investigating the pistons and changing them from one position to another was not as onerous a task. The top plate provided the necessary rigidity to support the weight of the test subject, without significant deflection allowing for more accurate readings from the RSscan foot pressure profile plate. The surface finish of the plywood top plate was rough enough to provide the necessary coefficient of friction so that the pressure profile plate or volunteer would not slide during testing.

A cubic framework made of one inch thick box aluminium was fixed to the platform giving users a railing at approximately waist height to reach for in the event of losing their balance. During testing users were required to keep their hands on their hips, so putting the railing at waist height ensured that they had the minimum distance to move their hands in the event of losing their balance. It was decided to use fixed safety rails. Foldable safety rails were rejected because they would be more susceptible to wear and tear especially at the joint and hence would carry an increased risk of failure with possible injury to the test subject.

3.1.2 Pneumatic actuators

Various designs that were considered for the actuation of the top plate included electromagnetic, motorised, pneumatic or hydraulic actuators. Pneumatic actuators were chosen after testing and cost examination was performed. The reasons for this are detailed below.

The electro magnetic actuators provided the necessary speed of motion and were relatively easy to control via the computer. They could be hooked directly into a power supply and they could be controlled directly via an RS232 cable. This system however was not used because the strength of the magnetic waves decreased at an exponential rate with distance from the magnet. Most of the electromagnetic actuators examined provided forces that were too low at a distance of just 10 to 20 mm. Any magnets within the budget for this project therefore proved to be unsuitable. Solenoids were considered and dismissed for similar reasons. There were electro-magnetic actuators available with the required range of motion (160mm) and force but their cost was excessive compared to that of the other solutions. A hydraulic solution could have provided the necessary force required for tilting a person. This solution was discounted due to the size of the equipment required, cost of this equipment and potential difficulties with maintenance.

A pneumatically actuated solution allowed for the necessary speed of tilt. The board could be tilted over and back within one second. This solution also allowed for tilting along multiple axes. The central joint of the motor actuated design presented in Chapter Two was discarded in this solution in favour of four universal joints on top of each piston. This allowed for tilting along multiple axes without placing undue strain on the system. Double acting cylinder pistons were chosen for use in this project work because they allowed the piston and thus the top plate to be accelerated upwards and downwards. Cushioned pistons were chosen because this feature prevented impact damage to the pistons if they were used full range. A piston of stroke length 0.16 m was chosen to provide the necessary tilting angle and for price vs. stroke length reasons. An inner diameter of 0.08 m on the piston was chosen as this shaft diameter would be able to move the 981 N load at an acceptable acceleration. The equations and calculations showing this are presented later in this chapter.

The base of the actuator was bolted to the base plate, the end effector for each of the four actuators was connected to the rod eye rotational joints which were in turn attached to the underside of the top plate. This setup allowed a maximum tilting angle of 18.4° from the piston stroke lengths of 160 mm. The piston actuators were equidistant from the top plate centre. These four pistons were located in a square pattern of edge length 500 mm, see figure 3.3 (b). Originally the pistons were placed at the median points of the square formation; see Figure 3.3 (a). However while this provided for greater range of motion in bi planar tiltings, it also meant that the top plate was unstable when raised. Once raised through one axis, the board would wobble by as much as +/-2° along the other axis. Moving the pistons to the corners provided greater stability but at the cost of reducing the maximum angle achievable on a diagonal tilt. This loss of range of motion was deemed acceptable because stability in a raised position was essential for the repeatability and experimental validity. Having the pistons at the corners meant that two of the pistons could be actively raised and the two opposing pistons actively held retracted, to provide tilting along either the X or Y axis.

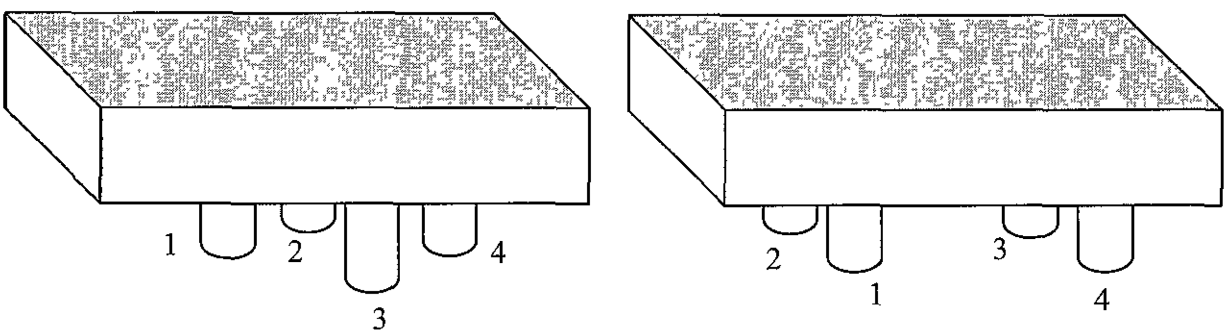

Figure 3.3 (a) Original piston positions and (b) final pistons positions.

The pressure plate readings that provide the most useful information to the physiologist, sport therapist or biomechanical researcher studying reactive balance are those readings taken immediately after a change in the board's position. Such readings should be able to measure the degree to which the subject was able to recover from an unexpected change to their balance and would only have been considered valid if also they were taken while the board was stable. A moving board would have constituted a sustained perturbance to the subject's balance and would not have shown the reaction to an unexpected once off event that was being looked for in this study. Thus for the purposes of this study the top plate had to be returned to the stable horizontal in under one second after it's initial upwards movement.

The readings would have been taken while the test subject was still on a moving surface and hence would not be indicative of the way a person would normally react after losing balance on stable ground. The use of double acting pistons which could be actuated upwards and downwards allowed for the top plate to be accelerated downwards, thereby reducing the time between initial perturbance and the top plates return to a stable horizontal position. This allowed the balance platform to be returned to a horizontal position within one second from a fully tilted position and hence reliable readings were obtained

The pistons had a built in cushioning effect which slowed down the movement at the top and bottom of actuator motion reducing the impact force that occurred when the piston reached the limits of its motion. For this project it was a requirement that the top plate would move at a high speed to perturb the person quickly enough to be able to test reactive balance and not the proactive balance as described in chapter one. To achieve this speed it was decided to reduce the cushioning effect by fully opening the valve that controlled the rate at which air escaped from the piston.

3.1.3 Pneumatic flow and relay system

Figure 3.4 depicts a flow chart showing how the control of the top plate was achieved by using a LabVIEW based control program. The LabVIEW program that was written to control eight different 5V digital control signals and two analogue control signals through a PCI, NI 6024E, LabVIEW DAQ (Data Acquisition) card.

The signals were connected via the breakout box. This is a terminal box which enabled connection of the relay based control circuit and the electro-pneumatic regulators to the DAQ card in the PC. The computer used was a Fujitsu Siemens Elonex with a 500MHz CPU and 512Mb of RAM.

Pneumatic valves were used to allow switching between the top and bottom ports of the pistons. A Sistem Block industrial air compressor was used to provide compressed air for the pistons. It had a tank capacity of 50 litres, with a rated motor power of 1.5kW and supplied up to 0.8MPa of pressure. Figure 3.5 outlines the pneumatic circuit and airflow from the compressor.

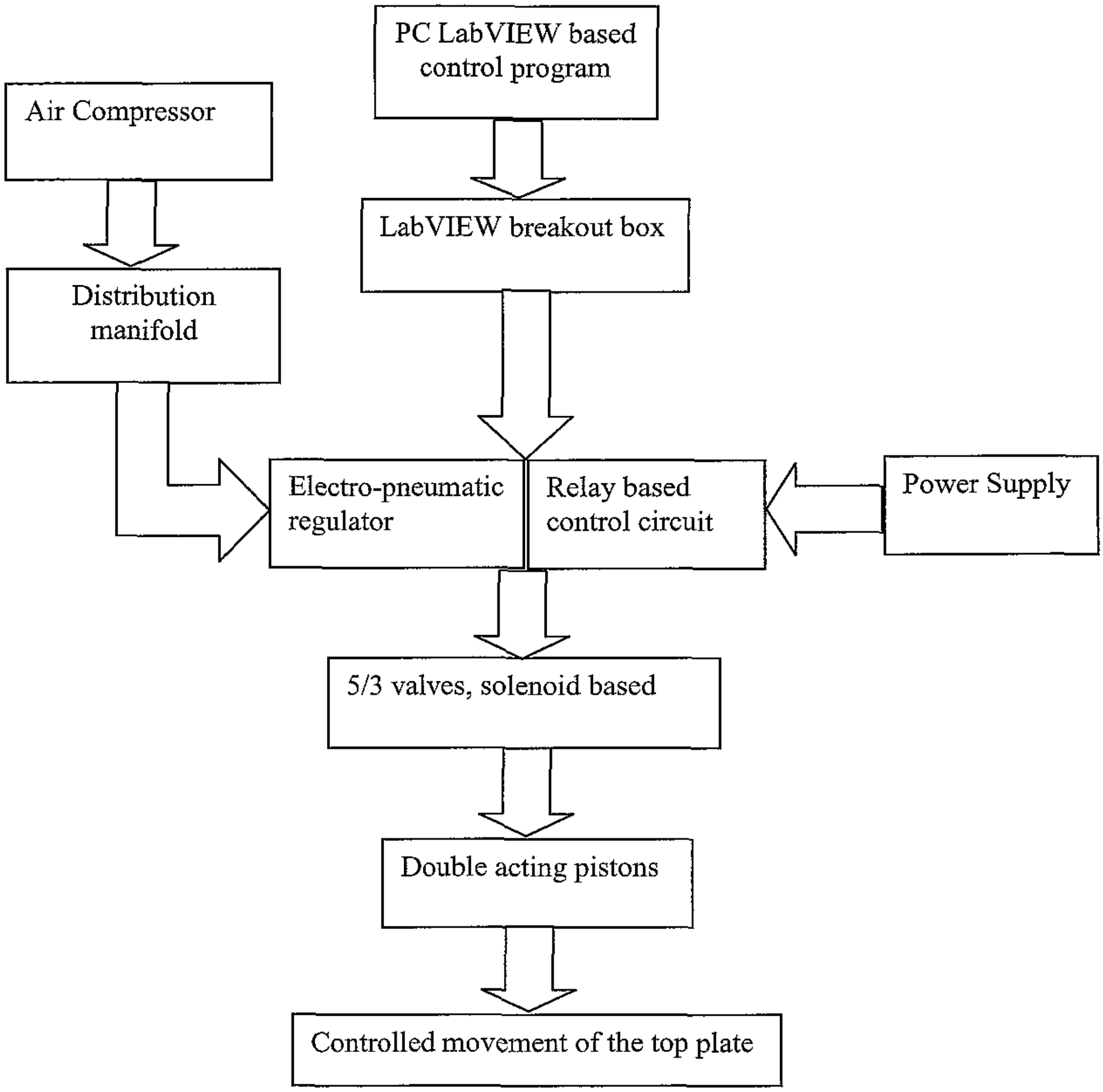

Figure 3.4 Flow chart for the operation of pneumatically actuated balance board.

A distribution manifold was used to split the airflow from the compressor into the required four separate output lines for the pistons. The distribution manifold was located centrally underneath the top plate to ensure that all hoses leading to the pistons could be of similar length. Having equal lengths of hosing to all four pistons meant that there was no need to adjust the timing of software signals to the 5/3 valves controlling the pistons. This was also done with the pressure regulators to ensure that timing was kept constant throughout changes in pressure levels as well as direction to the pistons. Differences in hose length would have resulted in the air from the compressor reaching two different pistons at asynchronous times. This in turn would lead to one piston rising a small time before another piston, which would result in the board tilting along two axes and not just one.

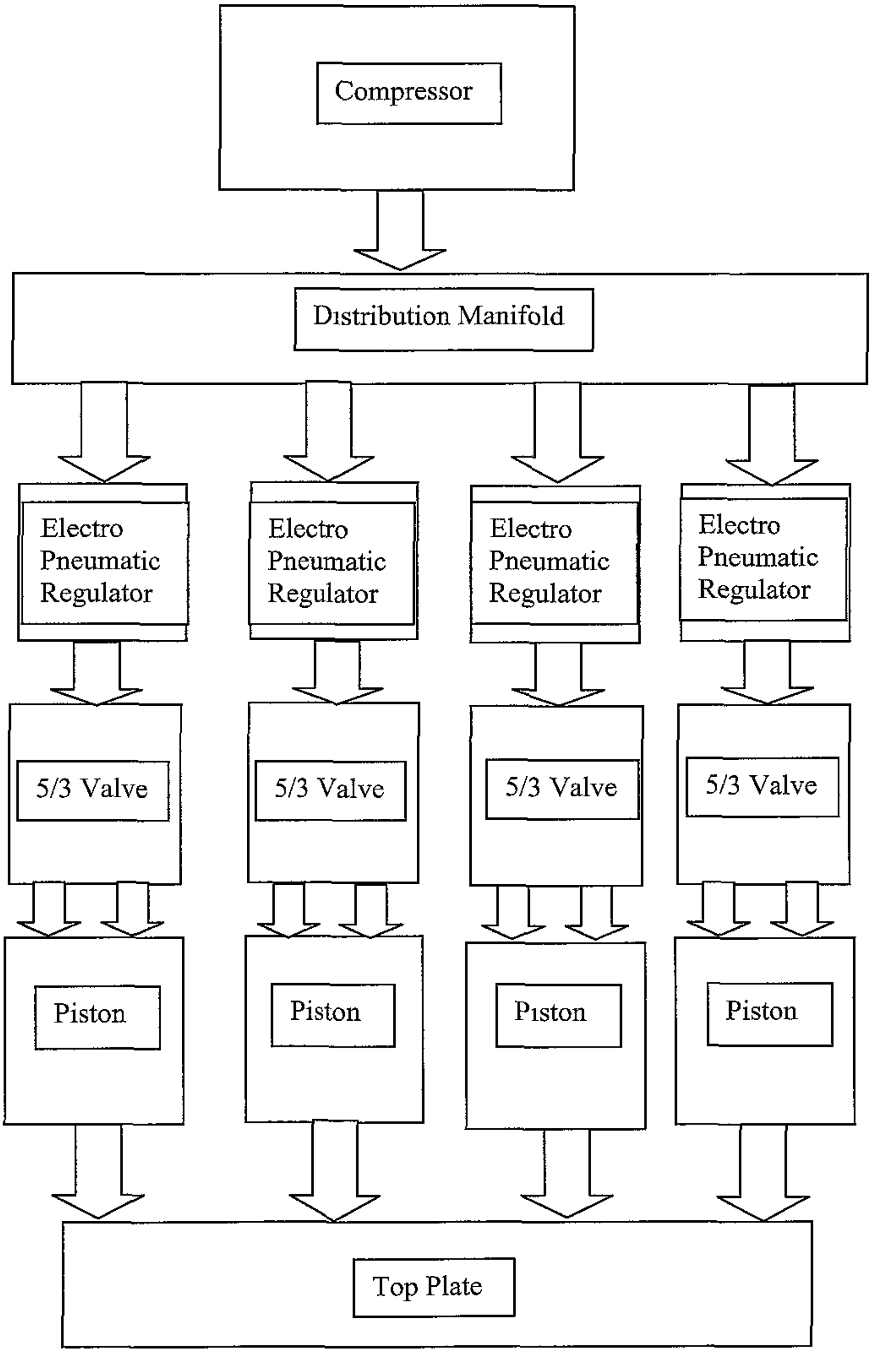

Figure 3.5 Pneumatic flow chart for balance platform

Electro-pneumatic regulators (ITV2050-21-3CS—Q) were used to provide a quick, computer control of the pressure of the air going into the pistons. They were rated to control a maximum pressure of 0.9 MPa through (9bar). This is shown in figure 3.5. These allowed for rapid changes in pressure to each piston which allowed much more dynamic movements to be created. The regulator worked on a linear scale and accepted analogue signals on the input line that determined the output pressure level. Figure 3.6 shows the regulator with ports one and two indicating the compressed air input and output respectively.

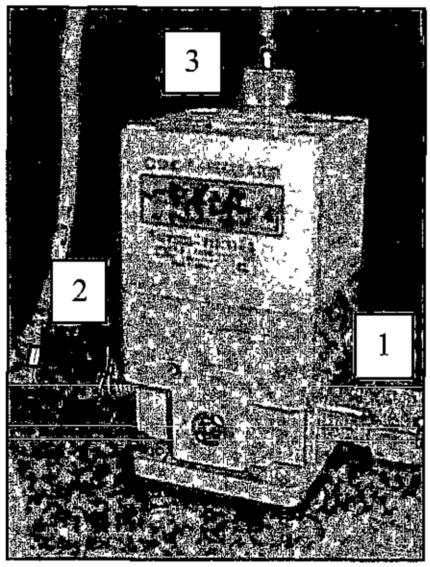

Figure 3.6 Electro pneumatic regulator with air lines (1-outlet and 2-inlet) and electronic control (3) shown.

The wire input labeled 3, is the electronic input and output and contains the 24V power supply required to run the regulator as well as the 5V analogue control signal and analogue feedback output signal. These also allowed the setting of the pressure levels were required for testing, see section 3.2.3.

The balance platform needed valves that would support three states – two states of activity that would allow movement of the pistons in either an upward or a downward direction, and a third neutral position in which no air was pumped to either the top or the bottom port. A 5/3 normally closed valve provided the three different states that the pistons required for this design. It was decided to use solenoid controlled valves instead of pneumatic ones as these afforded greater speed and easier interfacing with the controlling software. These five port valves are shown in Figure 3.7.

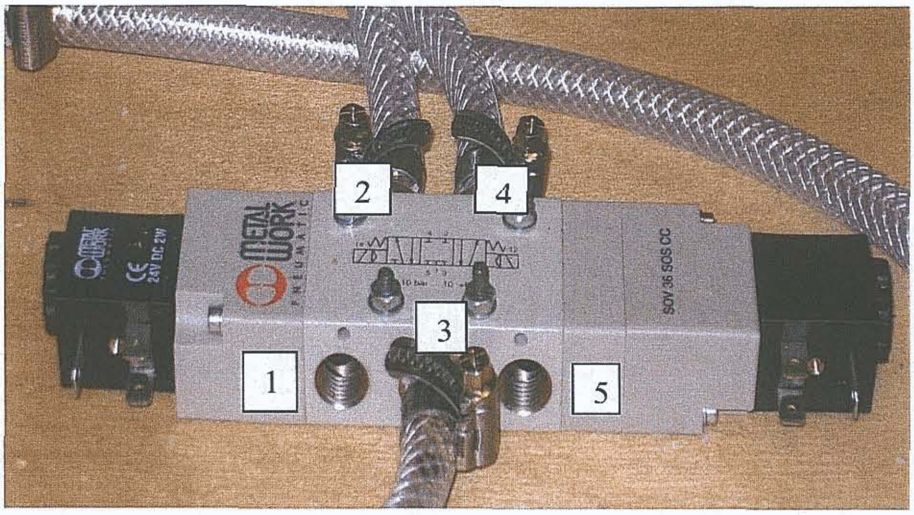

Figure 3.7 The 5/3 solenoid actuated pneumatic valve, with valve ports indicated.

The air from the compressor enters through port three of the valve and can then go either to the base of the piston through port two or into the top of the piston through port four. Ports one and five allow the piston to vent to the atmosphere and are connected to ports two and four respectively. The state of the valve, at any given time determines the manner in which these connections are made. The first state allows for upward motion. The air is pumped from the source entering through port three of the valve and goes through port two of the valve to the base port of the piston, driving the piston upwards. At the same time, port four is connected to port five allowing any air trapped in the piston from the previous cycle to vent out to the atmosphere. In the second state the air pumped from the source goes in through port three, on the valve, and out through port four to the top port of the piston while ports one and two are connected allowing the air used in the previous movement to vent out to atmosphere as the piston moves downward. These two states were selectable via the GUI control program developed and are activated when one of the solenoids on either side was powered. If neither solenoid was activated then the valve reverted to its neutral state. In this state the source is not connected to either of the output ports.

The valves are available in one of two different versions of the neutral state, normally open and normally closed. In normally open the two output ports two and four are connected to two ports one and five respectively and can be used in another process or allowed to vent directly to atmosphere. In normally closed ports two and four are not connected to anything and the air would remain trapped within the piston or any other device to which the valve was connected. The normally closed state was chosen for this project as it meant that at start-up or in the event of power loss, nothing would change within the system so there would be no sudden unexpected movements that could lead to injury.

Close positioning of the solenoid valves to the pistons was important for the machine to yield reliable results. There were several issues involved here. The solenoids needed to be placed far enough away from the pistons to ensure there were no 'kinks' in the tubing that could impede airflow. At the same time they needed to be close enough to allow for high tilting speeds of the top plate. The closer the solenoid to its assigned piston the faster air could be supplied or vented to or from the piston allowing for increased tilting speeds. As the system was designed to simulate an unexpected change to the person's centre of gravity, this increased responsiveness was a desirable.

3.1.4 PC control hardware and software

The computer used during this project was fitted with a PCI 6024E NI card and with LabVIEW software which was used to control the developed system. This card allowed for the required eight digital outputs and two analogue outputs and was connected via the breakout box to the circuitry of the balance board. Initial testing was done with the National Instruments, Measurement & Automation Program. This is a part of the NI package that allowed direct control of the analogue and digital inputs and outputs without the need for a control program. This facilitated initial testing to ensure that the relays, solenoids and electro-pneumatic regulators were working during all stages of the software development and provided a means of determining whether problems encountered were due to the LabVIEW control program or were hardware related. The final program was developed in stages beginning with the creation of a Front Panel (user interface) that allowed for on and off control of one piston, ensuring that this could be duplicated for all pistons, then extending the program, creating a front panel that could control two pistons again ensuring control of any two pistons, until in the final stage, control of all four pistons was achieved. Figure 3.8 shows the Front Panel developed for the motion control of one of the pistons. The corresponding Block Diagram (program coding) for this is shown in Figure 3.9.

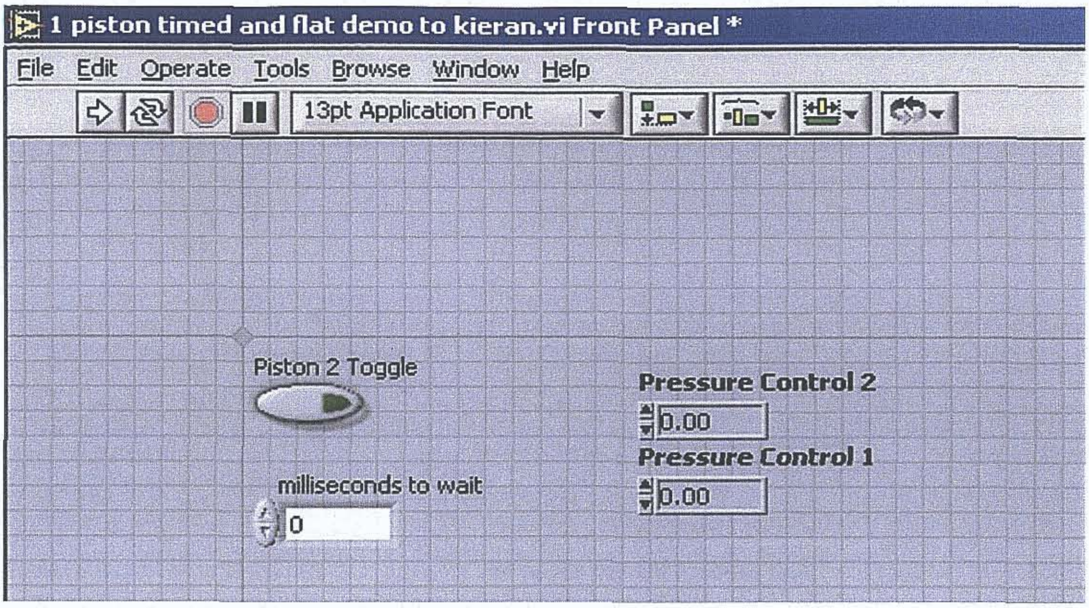

Figure 3.8 Front panel one piston controlled

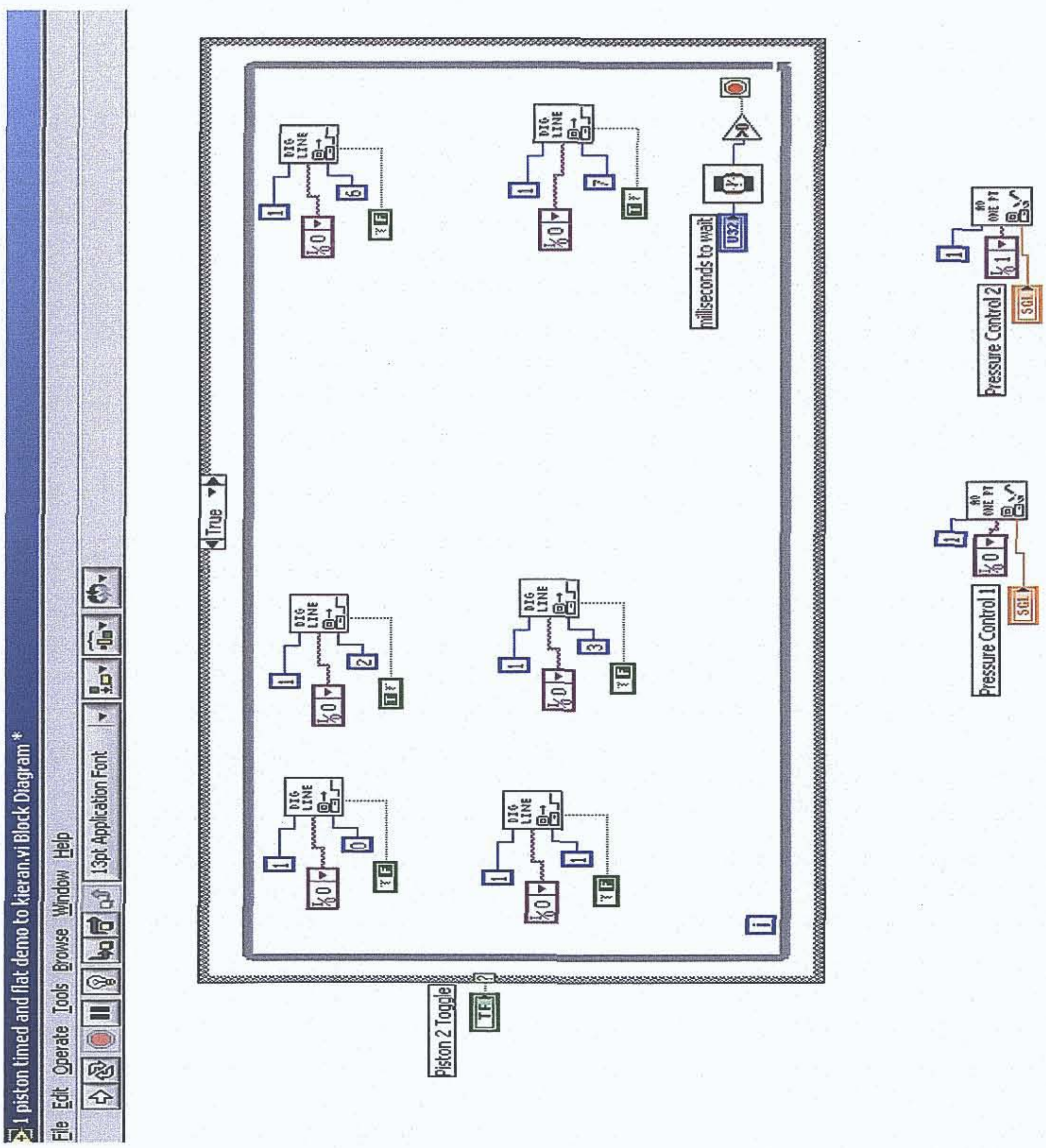

Figure 3.9 Control program block diagram for one piston, state 1 is shown

Control of four pistons however, created its own difficulties and required a program with a more intuitive interface with a series of Boolean switches. The Front Panel for this program is shown in Figure 3.10

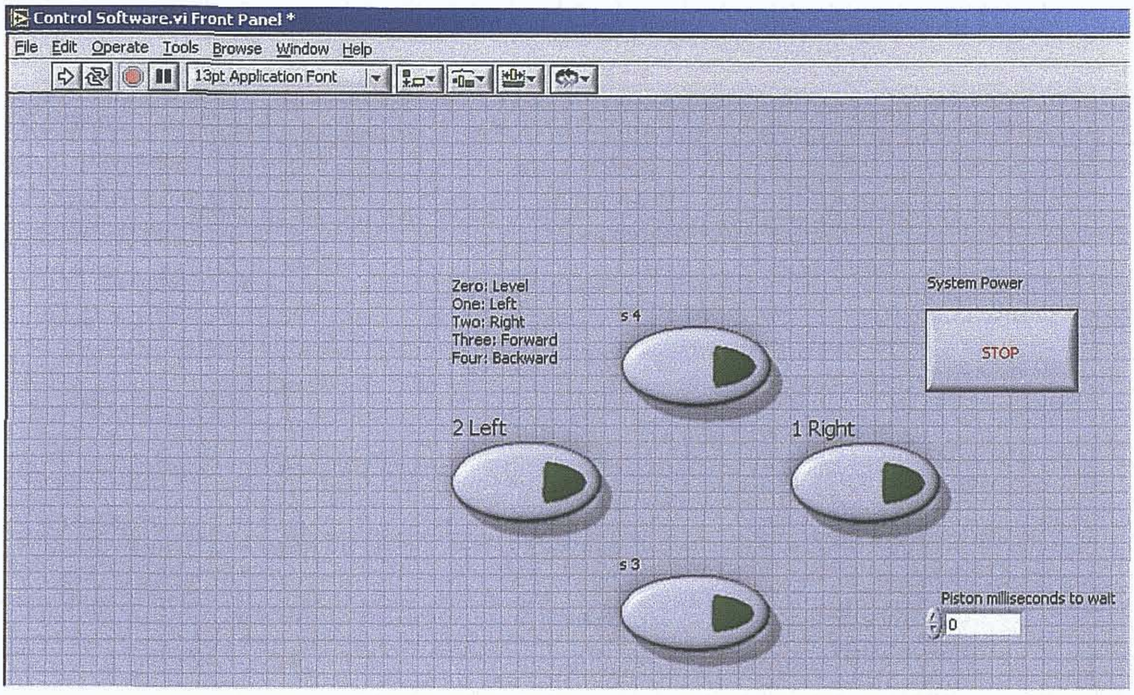

Figure 3.10 Front panel of final control program

The control program was based on having five separate states that were selectable from the Front Panel (GUI), shown in figure 3.10. Four of these states were for the four directions of tilt of the board - forward, backward, left and right. The fifth state was a neutral starting point to which the board would return at the end of each of the four other states. Within each of these states, the status of each relay and valve was explicitly defined to avoid problems that might occur if latching commands from one state carried over to the next. Figure 3.11 shows an earlier revision of the control program. In this initial program a buzzing noise was created as the relays flickered between one state and the next. This occurred due to the program loop rapidly iterating the relay between the on and off states. Figure 3.12 shows the initial neutral state for the final version of the control program.

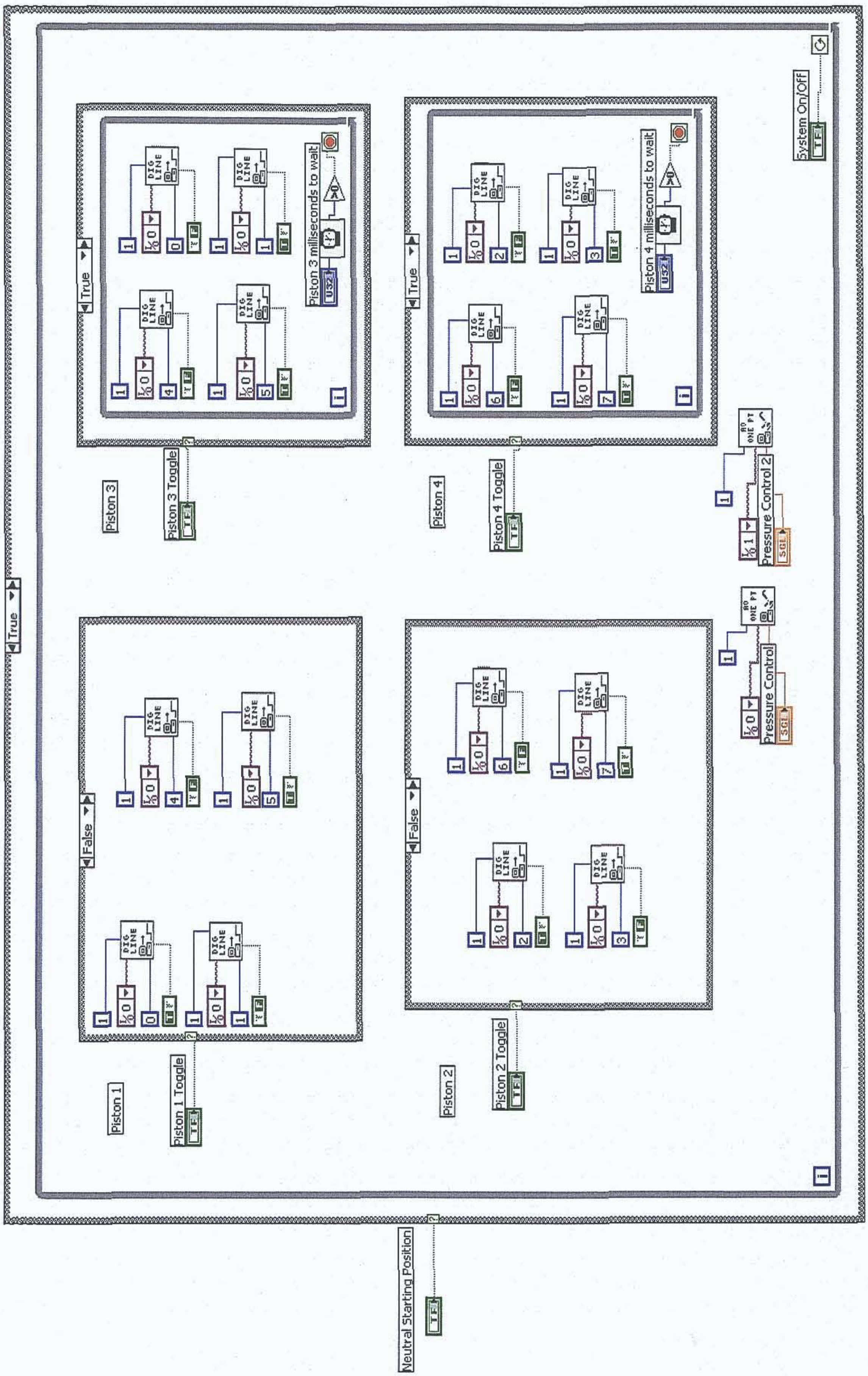

Figure 3.11 Case structure based control program

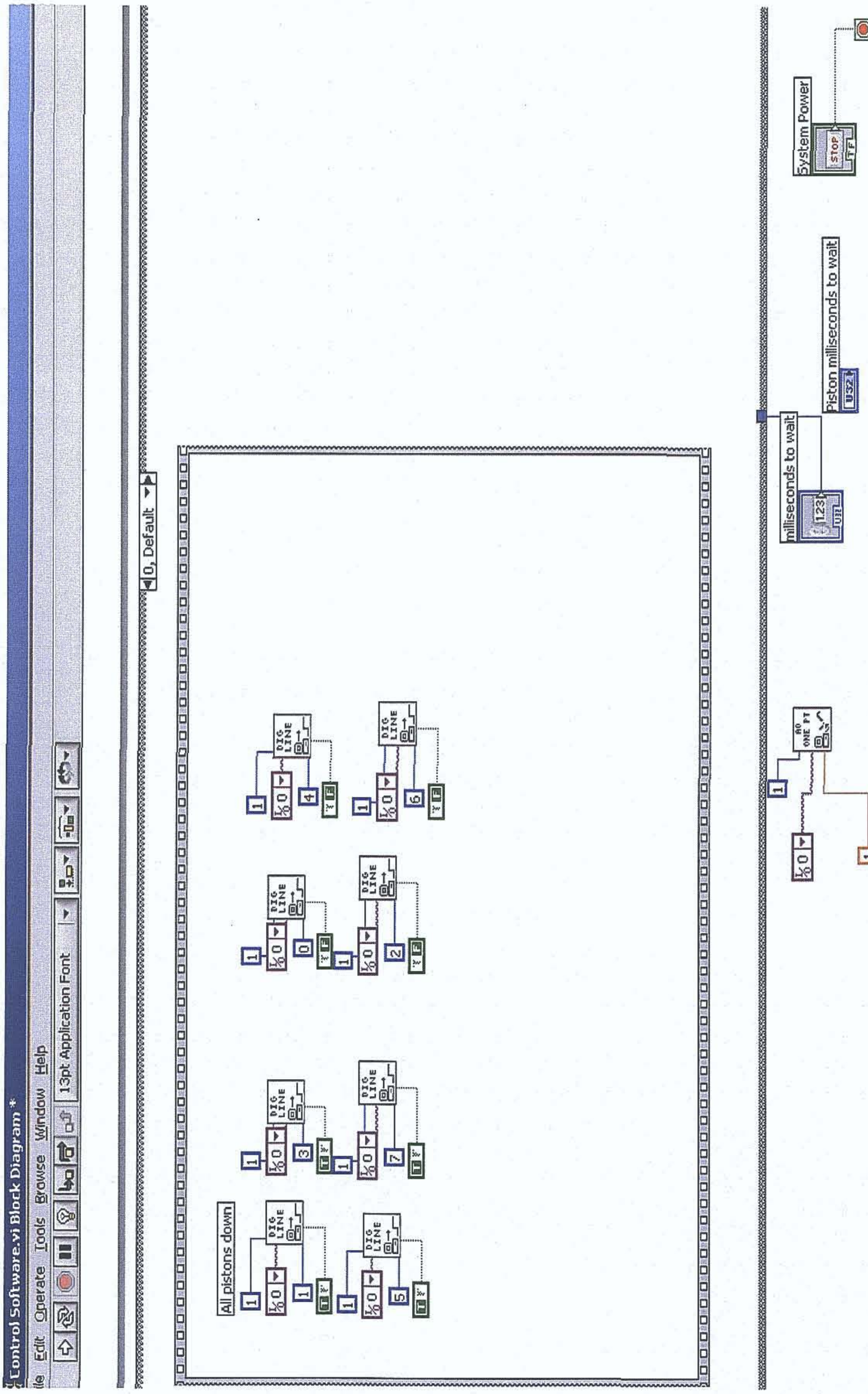

Figure 3.12 Initial neutral state for final control program

In one of the earlier programs, instructions given to the pistons in a while loop continued on after the loop was exited, causing unwanted results. For example to tilt to the right pistons one and two were activated upwards and a downward force was applied to pistons three and four. However, after this command was executed, if all four pistons were activated downward, the board would not move but would remain in the position tilted to the right. The problem was rectified by adding more instructions to control the air flow to the pistons and to discontinue the upward force to pistons one and two when returning the top plate to the neutral horizontal position. For every movement all eight states for the four pistons had to be defined, as the hardware retained commands from the previously set state.

Once control of the board was achieved via a numeric input, a more intuitive control panel with a series of Boolean switches was needed. This was implemented by using the Select function in LabVIEW which allowed for the selection of various system states or, as in this case, various movements of the top plate. For the testing, it was necessary that the board be set to the neutral (horizontal) state between tilting actions of the top plate. This became the default state to which all other states reverted on completion of a specified action.

The problem with the version shown in figure 3.11 was overcome by the use of flat sequence structures inside of a case structure. The case structure allowed the commands to the four pistons to be stored in four separate cases while the flat sequence structure allowed two distinct phases to occur within each of these cases, separating the commands for the raising and lowering of each piston further into two phases. Thus the full eight motions used could occur at separate times eliminating the buzzing. This buzzing was created by the rapid switching of the relays on and off, as the program continuously switched between states.

The final program worked by using an initial condition shown in figure 3.12 from which all of the movements began and ended. This state was the neutral condition mentioned above, in which the pistons were returned to a fully retracted state and all pressure was stopped to both ends, leaving them ready for the next command.

This condition was considered necessary as a safety factor because it ensured that upon starting the program, all previous commands were cleared and the board was set to or kept in the neutral horizontal position until the tester was ready for the top plate to tilt in the desired direction. Without this, the issuing of the LabVIEW stop program command would halt the program instantly without allowing completion of the current set of instructions. These instructions would then be held in memory until the program was next executed and would run ahead of any new instructions.

As a further safety feature, there was an overall on/off switch built into the program to prevent any accidental movements. When this was in the off state no other features worked. This switch once pressed allowed the program to complete its current list of tasks before stopping and prevented any tasks being held over in memory as mentioned in the previous paragraph.

From this initial neutral condition, the user could select one of four separate states for the program tilting to the left, right, forwards or backwards, by clicking on one of the four arrow buttons on the front panel. These buttons were the four Boolean switches that were used to select one of the four case states and to make the program as intuitive as possible; they were aligned to correspond to the directions of tilt they would produce in the top plate. This can be seen in figure 3.10.

The four selectable states each had a rising and a falling stage. To control the time of the while loop, there was a timer accessible from the front control panel by the "Piston milliseconds to wait" numeric control. Once this first loop was finished, the program entered the second stage of the flat sequence structure in which another condition timer controlled the while loop. This was used to return the top plate to the horizontal before passing control back to the initial neutral condition. A second numeric control on the block diagram allowed the user to decide what pressure would be used for that movement by entering a value that represented barometric pressure. When the tests were performed with volunteer test subjects, this was set to 0.2 MPa (2 bar). Testing conditions are discussed further in Chapter Four. To simplify operation of the platform the pressure control was kept hidden on the front panel but can be seen in the block diagram in Figure 3.13. This also shows the flat sequence structure that was used within a case structure to allow for the multiple selectable modes, directions of tilt, to have more than one stage of movement, i.e. movement upwards and downwards.

The final program had to interface with the control software for the RSscan pressure plate. To achieve this, an analogue trigger signal was needed. It needed to be capable of sending a TTL voltage of between 0.7V and 3.2V, a square waveform pulse that transitioned from high to low in less than 200ms. Triggering occurred on the rising edge of this pulse. LabVIEW was able to simulate this signal with 2.5V being used and transition occurring within 10ms.

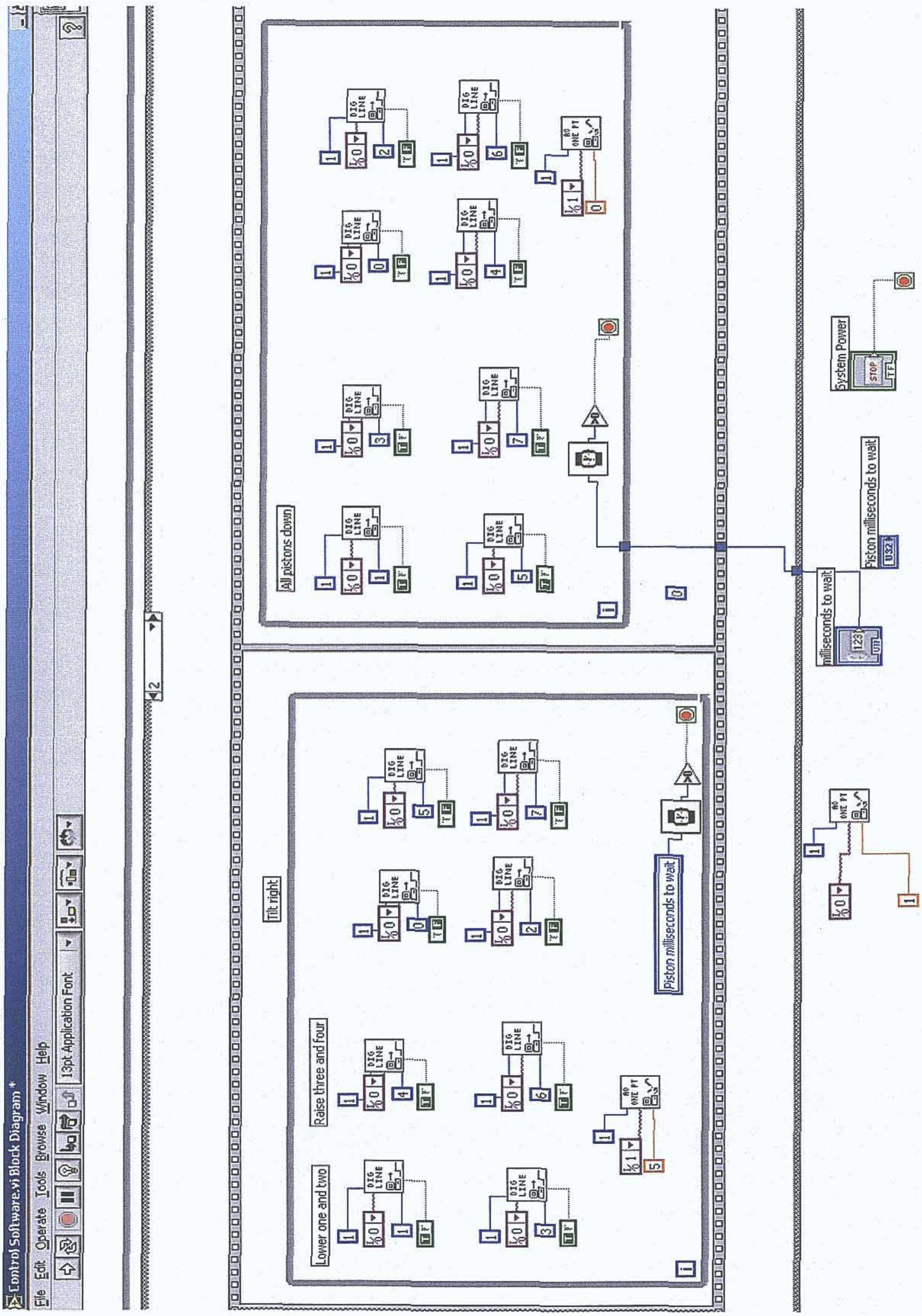

Figure 3.13 One of the four movement states of the final version control program

There were three main criteria used in selecting the relays - switching speed, energy consumption and price. The price of all the relays examined was low and as only eight were required this turned out not to be a main concern. The switching speed on the selected model was 2.5ms. This was one of the fastest speeds of the relays considered. The switching speed of the relay influenced the time it took for changes made through the control software to have an effect on the angle of the Top Plate.

The second criterion considered in relay selection was power consumption. The relay chosen needed a minimum supply current of 28.5mA to trigger a change of state. The PCI version of the LabVIEW card, was able to supply the necessary current on its digital input/output ports but the USB version could only supply 8.5 mA. This meant that the USB DAQ could not provide enough current to switch the relays and so the PCI version was used.

3.2 Analysis of pneumatic design

3.2.1 Mechanics of the top plate

(Deflection of top plate for various loading levels – Theory)

This section examines the deflection of the top plate under the expected loading conditions. Accuracy of results collected by a pressure plate required that the top plate should undergo minimal deflection. Any deflection in the top plate surface would affect the ability of the pressure plate to accurately read the pressure upon it. Figures 3.14 and 3.15 indicate the forces acting on the top plate. The derivation of this bending moment shear force is given below.

Nomenclature:

w = weight / unit length

wL = weight of beam

W = weight of person

R_a = reaction at A

R_b = reaction at B

From symmetry $R_a = R_b = 1/2(W + wL)$

M = bending moment

F_{shear} = shear force

v = deflection from the horizontal at distance x from the end

C = constant of integration

E = Young's modulus for plywood

I = moment of inertia

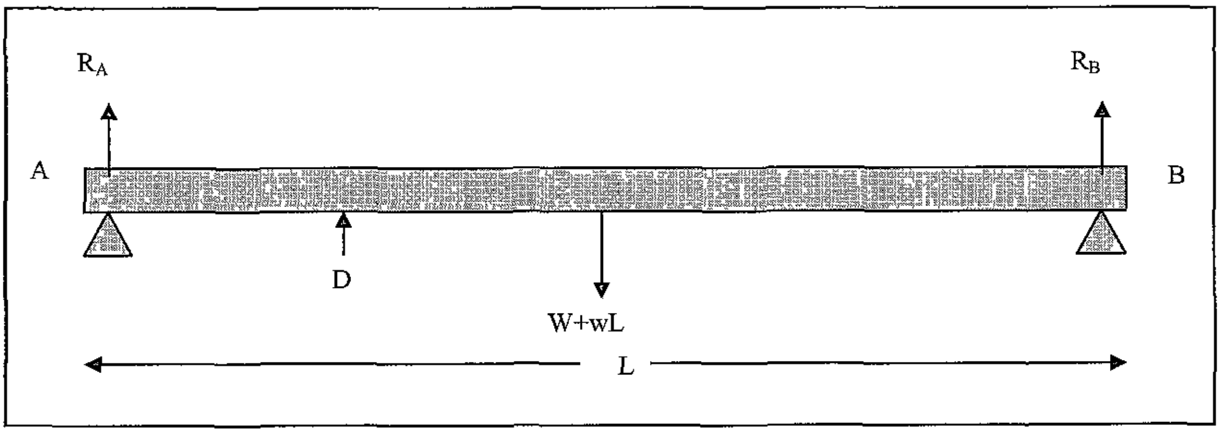

Figure 3.14 Outline of forces acting on top plate

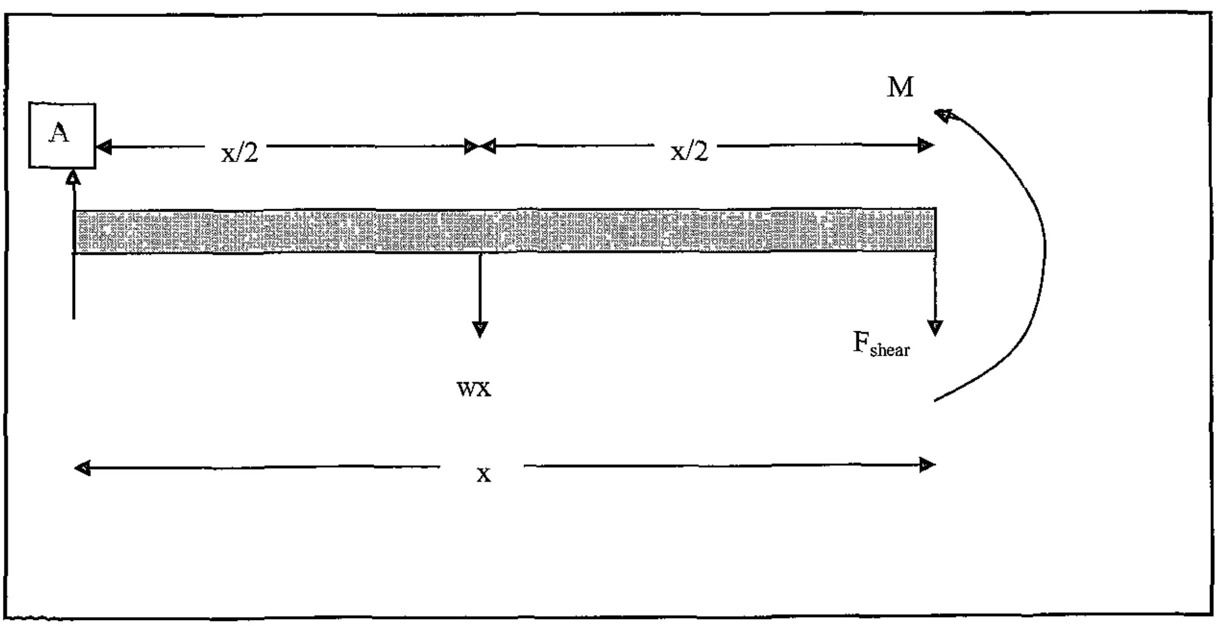

Figure 3.15 FBD for top plate

$$0 < x < \frac{L}{2}$$

Taking moments about D; D being any point between A and the midpoint at a distance x from A,

$$M + \ wx\ (\frac{x}{2}) - \frac{1}{2}(W + wL)x = 0$$

$$M = \frac{1}{2}(W + wL)x - \frac{wx^2}{2}$$

$$EI\frac{d^2v}{d\ x^2} = -M$$

$$EI\frac{d^2v}{dx^2} = \frac{wx^2}{2} - \frac{1}{2}(W + wL)x \qquad (2.1)$$

Integrate

$$EI\frac{dv}{dx} = \frac{wx^3}{6} - \frac{1}{4}(W + wL)x^2 + C_1 \qquad (2.2)$$

$$EIv = \frac{wx^4}{24} - \frac{1}{12}(W + wL)x^3 + C_1x + C_2. \qquad (2.3)$$

$v = 0$ when $x = 0,\ C_2 = 0$

When x = ½L and dv/dx = 0 the maximum deviation occurs.

From equation 2.2

$$0 = \frac{w}{6}\left(\frac{L}{2}\right)^3 - \frac{1}{4}(W + wL)\left(\frac{L}{2}\right)^2 + C_1$$

$$\frac{WL^2}{16} + \frac{wL^3}{16} - \frac{wL^3}{48} = C_1$$

$$C_1 = \frac{WL^2}{16} + \frac{wL^3}{24}$$

$$EIv = \frac{wx^4}{24} - \frac{1}{12}(W + wL)x^3 + \left(\frac{WL^2}{16} + \frac{wL^3}{24}\right)x$$

v is max when x = ½ L

$$EIv_{max} = \frac{w}{24}(\frac{L^4}{16}) - \frac{1}{12}(W + wL)\frac{L^3}{8} + \frac{L^2}{48}(3W + 2wL)\frac{L}{2}$$

$$v_{max} = \frac{L^3}{96EI}\{\frac{wL}{4} - W - wL + 3W + 2wL\}$$

$$v_{max} = \frac{L^3}{96EI}\{2W + 5\frac{wL}{4}\}$$

$$v_{max} = \frac{WL^3}{48EI} + \frac{5wL^4}{384EI} \qquad (2.4)$$

v_{max} = deflection caused by the weight of the person and by the weigh of the beam

Deflections on the right of centre = deflections on the left of centre.

In the case of this current design,

W = a maximum of 981 N (for 100kg person)

L = 0.50 m

w = 30 kg (weight of top plate)

I = 1.3655×10^{-6} [Ref: 70]

E = 12.4 GPa [Ref: 71]

$$v_{max} = \frac{WL^3}{48EI} + \frac{5wL^4}{384EI}$$

$$v_{max} = \frac{100 * 9.81 * (0.5)^3}{48 * (16.3922 * 10^3)} + \frac{5 * 30 * 9.81 * (0.5)^3}{384 * (16.3922 * 10^3)}$$

$$v_{max} = 0.1508 * 10^{-3} + 0.0283 * 10^{-3}$$

$$v_{max} = 0.1791 * 10^{-3} m$$

This 0.1791mm was considered to be an acceptable level of deflection.

3.2.2 Characterisation of top plate motion control – Theory (Speed, Acceleration and Angle characterisation of system)

It was necessary to know how much force was being generated with one and two pistons depending on the pressure applied. This allowed the calculation of velocities and accelerations that the test subject underwent during tilting and allowed for the calculation of the pressures needed to achieve similar conditions for a variety of different test subject weights. Table 3.1 shows the forces generated by the pistons for various set pressures.

Values of the maximum force from one and two pistons are tabulated for a variety of pressures. The top plate assembly weighed approximately 40kg and provided an approximate downward force of 400N. In this build the top plate consisted of two 1" thick sections of marine plywood whereas previously it consisted of 2 ¾" thick sections of marine plywood. The net force from activation of one or two piston is also given. Using only one piston to actuate the top plate produces a diagonal (along the x and the z axis as shown in figure 2.4) tilting motion whereas tilting with two pistons provides tilting the x axis or z axis. The pressure can be calculated as follows. Equations 3.5 to 3.8 were used to calculate the forces acting on an unloaded top plate and are tabulated for a variety of different pressures in Table 3.1.

Gross and net force provided during one and two piston tilting motions

P – Pressure supplied by the compressor to the pistons.

F_1 – Upward force provided by one piston.

F_2 – Net force acting on test subject with one piston

F_3 - Upward force provided by two pistons

F_4 - Net force acting on test subject with two pistons

d – Internal diameter of each piston.

K – System losses due to weight of top plate (50.97 kg)

$$F_1 = P * \left(\frac{d}{2}\right)^2 * \pi \qquad [3.5]$$

$$F_2 = \left[P * \left(\frac{d}{2}\right)^2 * \pi\right] - K \qquad [3.6]$$

$$F_3 = \left[P * \left(\frac{d}{2}\right)^2 * \pi\right] * 2 \qquad [3.7]$$

$$F_4 = \left\{\left[P * \left(\frac{d}{2}\right)^2 * \pi\right] * 2\right\} - K \qquad [3.8]$$

Pressure (MPa)	F_1, Total upward force (N) 1 piston	F_2, Net upward force (N) 1 pistons	F_3, Total upward force (N) 2 pistons	F_4, Net upward force (N) 2 pistons
0.1	453.56	-46.433	907.13	407.13
0.2	907.13	407.13	1814.26	1314.26
0.3	1360.70	860.70	2721.40	2221.40
0.4	1814.26	1314.26	3628.536	3128.53
0.5	2267.83	1767.83	4535.67	4035.67
0.6	2721.40	2221.40	5442.80	4942.80
0.7	3174.96	2674.96	6349.93	5849.9
0.8	3628.53	3128.53	7257.07	6757.07
0.9	4082.10	3582.10	8164.20	7664.206

Table 3.1 Total force supplied by each piston and net force after losses

Lateral and frontal as stated in the tables below refers to tilting involving the use of two pistons whereas diagonal tilting involves the use of one piston. Table 3.2 shows the net force that was used to accelerate the top plate through its tilting motion after system losses and taking account of the test subject's weight. Equation nine shows how F_5 was calculated and the calculation of for F_6, F_7, F_8, F_9 and F_{10}, values can be inferred from reference to table 3.1

$$F_5 = F_4 - W \quad [3.9]$$

F_5 Net force after loading on top plate with two pistons at 0.2MPa

F_6, Net force after loading on top plate with two pistons at 0.5MPa

F_7, Net force after loading on top plate with two pistons at 0.8MPa

F_8, Net force after loading on top plate with one piston at 0.2MPa

F_9 Net force after loading on top plate with one piston at 0.5MPa

F_{10} Net force after loading on top plate with one piston at 0.8MPa

W Weight of test subject in Newtons

W, Test subject weight (N)	F_5, Net force (N) for lateral or frontal tilting at 0.2MPa	F_6, Net force (N) for lateral or frontal tilting at 0 5MPa	F_7, Net force (N) for lateral or frontal tilting at 0.8MPa	F_8, Net force (N) for diagonal tilting at 0.2MPa	F_9, Net force (N) for diagonal tilting at 0.5MPa	F_{10}, Net force (N) for diagonal tilting at 0 8MPa
392.0	922.26	3643 67	6365.07	15.13	1375.83	2736 53
490.0	824.26	3545.67	6267.07	-82 86	1277.83	2638 53
589 0	725.26	3446 67	6168.07	-181.86	1178.83	2539.53
687 0	627.26	3348 67	6070.07	-279.86	1080 83	2441.53
785 0	529.26	3250 67	5972.07	-377.86	982.83	2343 53
883 0	431.26	3152 67	5874 07	-475.86	884.83	2245.53
981 0	333.26	3054.67	5776.07	-573.86	786.83	2147.53

Table 3.2 Net force for three different pressures with single and dual piston tilting

Estimated frictional forces, minimal force required to raise the top plate and the force available after friction with maximum available pressure are discussed in greater detail in Chapter Three. The accelerations of the top plate were calculated as indicated below in equation 3.10

A_1 Net acceleration after loading on top plate with one piston at 0.2MPa

A_2, Net acceleration after loading on top plate with one piston at 0.5MPa

A_3, Net acceleration after loading on top plate with one piston at 0.8MPa

A_4, Net acceleration after loading on top plate with two pistons at 0.2MPa

A_5 Net acceleration after loading on top plate with two pistons at 0.5MPa

A_6 Net acceleration after loading on top plate with two pistons at 0.8MPa

M_1 Mass of top plate

g Acceleration due to gravity

$$F = ma$$

$$(A_1 \; to \; A_6) = \frac{(F_5 \; to \; F_{10}) - W}{M_1 + K} \quad [3.10]$$

Equation 3.10 was used to calculate acceleration values for A_1-A_6, shown in table 3.3 by selecting the appropriate force from table 3.2 and the using the appropriate weight for the test subject.

W, Test subject weight (N)	A_1, Net acceleration (m/s^2) for diagonal tilting at 0.2MPa	A_2, Net acceleration (m/s^2) for diagonal tilting at 0 5MPa	A_3, Net acceleration (m/s^2) for diagonal tilting at 0 8MPa	A_4, Net acceleration (m/s^2) for lateral or frontal tilting at 0.2MPa	A_5, Net acceleration (m/s^2) for lateral or frontal tilting at 0.5MPa	A_6, Net acceleration (m/s^2) for lateral or frontal tilting at 0 8MPa
392.000	0 166	15.124	30.082	10.138	40 054	69 970
490.000	-0 821	12.656	26.132	8.164	35 117	62.070
589.000	-1.639	10.623	22.885	6.536	31.060	55 584
687.000	-2.314	8.935	20.183	5.185	27.682	50 179
785.000	-2 885	7.504	17.894	4.041	24.820	45 599
883.000	-3 376	6.277	15 929	3.059	22 364	41.669
981.000	-3 801	5 212	14 225	2.208	20 234	38.260

Table 3.3 Net acceleration with no load for single and dual piston tilting

Table 3.4 shows the force needed to achieve three set acceleration for different test subject weights. This was derived using equation 3.10.

$F_{11,12,13}$ Force from each piston to achieve preset acceleration with 2 pistons

$A_{7,8,9}$ Preset acceleration

M_2 Mass of test subject

$$F_{11,12,13} = \frac{[(M_2 + k)*(A_{7,8,9})]}{2} \qquad (3.11)$$

Test subject weight (N)	F_{11}, Force (N) needed for $10m/s^2$ acceleration with 2 pistons	F_{12}, Force (N) needed for $25m/s^2$ acceleration with 2 pistons	F_{13}, Force (N) needed for $50m/s^2$ acceleration with 2 pistons
392.0	909.68	2274.21	4548 42
490.0	1009.68	2524.21	5048.42
589 0	1109.68	2774.21	5548 42
687.0	1209 68	3024.21	6048.42
785.0	1309.68	3274.21	6548.42
883 0	1409 68	3524.21	7048.42
981.0	1509 68	3774.21	7548.42

Table 3.4 Force needed to keep upward acceleration equal for three different accelerations

Table 3.5 lists the pressures necessary to keep the same acceleration for the three preset accelerations, A_7, A_8 and A_9, with a range of test subject weights ranging from 40kg to 100kg and increasing in 10kg increments. This table could then be entered into the LabVIEW control program and used by it to provide a more uniform perturbance to the test subject. The aim would be to have the control program reference an equation that would take into account the volunteer's weight and set an appropriate pressure. The volunteer's weight would be entered via another dialogue box by the tester.

P_1 to P_6 Pressure required to achieve preset accelerations A_7, A_8 or A_9 with one or two piston *tilting*

r radius of the inner shaft of the piston

$$P_1 \; to \; P_6 = \frac{F_{11} \; to \; F_{16}}{r^2 * \pi} \qquad [3.11]$$

It can also be seen from this that certain accelerations are not achievable using single piston tilting.

Test subject weight (N)	Pressure P_1, (bar) needed for 10m/s^2 acceleration with 2 pistons	Pressure P_2, (bar) needed for 25m/s^2 acceleration with 2 pistons	Pressure P_3, (bar) needed for 50m/s^2 acceleration with 2 pistons	Pressure P_4, (bar) needed for 10m/s^2 acceleration with 1 piston	Pressure P_5, (bar) needed for 25m/s^2 acceleration with 1 piston	Pressure P_6, (bar) needed for 50m/s^2 acceleration with 1 piston
392 0	1.00	2 50	5.01	2.00	5 01	10.02
490 0	1 11	2.78	5.56	2 22	5 56	11.13
589 0	1 22	3.05	6 11	2.44	6 11	12 23
687.0	1 33	3.33	6 66	2.66	6.66	13 33
785 0	1.44	3.60	7.21	2.88	7.21	14.43
883.0	1.55	3.88	7.77	3.10	7.77	15 54
981.0	1 66	4.16	8.32	3.32	8.32	16.64

Table 3.5 Pressures needed to keep upward acceleration equal for three different preset accelerations

F_{14} Net force after system losses for a set test subject weight at 0.2MPa

F_{15} Net force after system losses for a set test subject weight at 0.5MPa

F_{16} Net force after system losses for a set test subject weight at 0.8MPa

J_1 Percentage difference in force between loaded and no loading

$$F_{14,15,16} = F_2 - W \quad (3.12)$$

$$J_1 = F_{14,15,16} - F_2 \quad (3.13)$$

Table 3.6 shows the difference in net force for three preset pressure values and compares these values to the net upward force for the no loading situation. This allows the user to compare the force possible from the machine with the force available when a test subject is on the balance platform.

Weight of test subject (kg)	F_{14}, Actual net force (N) at 0.2MPa	F_{15}, Actual net force (N) at 0.5MPa	Percentage difference from no loading, J_1	F_{16}, Actual net force (N) at 0 8MPa	Percentage difference from no loading, J_2
40.0	15 13	1375.83	22.17	2736.53	12 53
50 0	-82 86	1277 83	27.71	2638.53	15.66
60 0	-181.86	1178 83	33.31	2539 53	18.82
70 0	-279.86	1080.83	38.86	2441 53	21 95
80 0	-377.86	982.83	44 40	2343 53	25.09
90 0	-475 86	884.83	49.94	2245.53	28 22
100.0	-573.86	786.83	55 49	2147 53	31 35

Table 3.6 Percentage changes in net upward for 2, 5 and 8bar respectively for diagonal movements of the top plate.

As can be seen from the results tilting at 0.2MPa (2bar) is not a viable option for diagonal tilting of the top plate with an adult of normal, healthy weight.

F_{17} Net force after system losses for a set test subject weight at 0.2MPa

F_{18} Net force after system losses for a set test subject weight at 0.5MPa

F_{19} Net force after system losses for a set test subject weight at 0.8MPa

As can be seen from table 3.8 as the pressure supplied to the pistons goes up the percentage difference between the net upwards force and the no loading situation with a similar force decreases. At 0.2MPa (2bar) pressure the difference ranged from 49% to 81% indicating an initial force difference range of 32% when compared to the no loading situation. At 0.5MPa (5bar) pressure ranged from 19% to 32% giving a difference of 13%. Finally, at 0.8MPa (8bar) the pressure ranged from 12% to 20%, giving a pressure difference of 8%. These differences in pressure are discussed further in chapter five.

Weight of test subject (kg)	F_{17}, Actual net force (N) at 0.2MPa	Percentage difference from no loading	F_{18}, Actual net force (N) at 0 5MPa	Percentage difference from no loading	F_{19}, Actual net force (N) at 0 8MPa	Percentage difference from no loading
40.000	922.268	49 166	3643 670	19.666	6365.072	12.291
50.000	824.268	54.567	3545 670	21.827	6267 072	13.642
60.000	725 268	60 024	3446.670	24.010	6168 072	15.006
70.000	627 268	65.426	3348.670	26.170	6070 072	16.356
80.000	529 268	70 827	3250.670	28.331	5972.072	17.707
90.000	431.268	76.229	3152.670	30 492	5874.072	19.057
100 000	333.268	81.631	3054.670	32.652	5776 072	20.408

Table 3.7 Percentage changes in net upward force for 2, 5 and 8 bar respectively for lateral and frontal movements

3.2.3 Characterisation of top plate motion control – Experiments (Speed, Acceleration and Angle characterisation of system)

One of the main concerns of the project was repeatability for the sake of experimental validity. If the platform was not capable of reproducing the same conditions for a variety of test subjects then it could not have reliably been used to generate useful scientific data in the fields of medicine and sports science. Hence the platform was designed to be able to reproduce the same angles and initial forces that caused movement for a variety of test subjects.

To test for repeatability of angles and speeds, a number of recordings were taken for various pressures and times and loadings. The Citius C10 high speed camera shown in figure 3.16 was setup on a horizontal platform placed exactly 2m from the edge of the top plate, setup shown in figure 3.17.

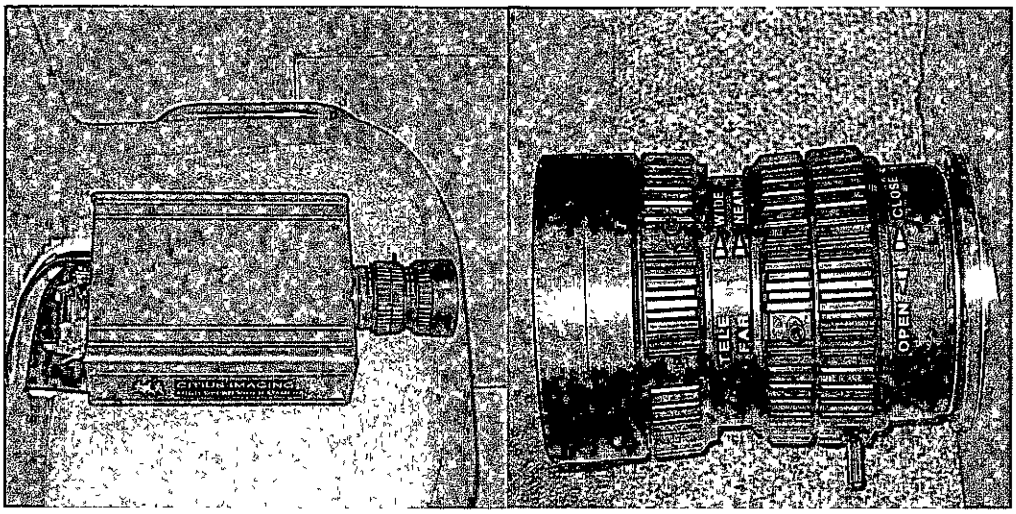

Figure 3.16 High speed camera used for analysis and close-up of lens

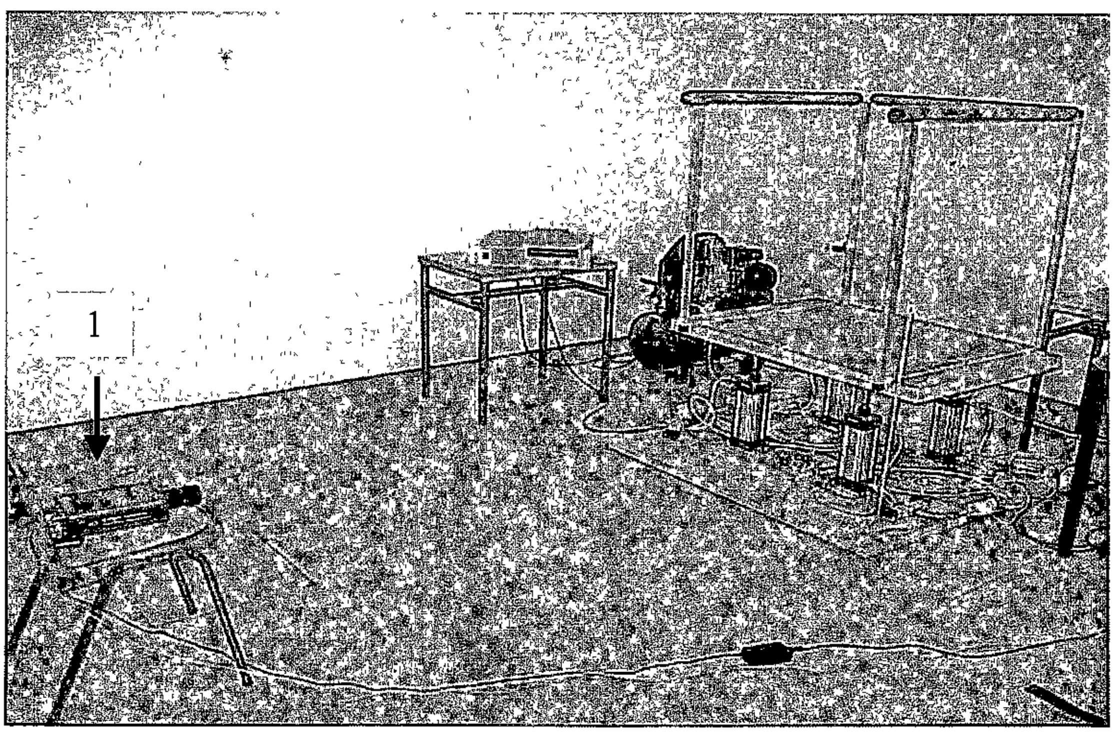

Figure 3.17 High speed camera analysis setup

The high speed camera was set to record at the highest possible resolution, 640x480, at a frame rate of 100 frames/s. This was considered sufficient for the purposes of this project because the movement in any one direction was set to 0.25s, and this allowed 25 frames to be captured of this motion which was sufficient to calculate velocities and acceleration. The camera captured the entire edge of the top plate which was needed for all the calculations on angles and times. The ½" C-mount lens was manually focused on the platform. The camera was capable of achieving speeds of up to 10652 frames/second at resolutions of 40x20 pixels. The highest resolution possible at the lowest speed setting was 652x496 pixels. The camera was set via the supplied Citius software to record at 100 frames/second and a resolution of 640x480 pixels. Recording times were set via the computer. With 256 Mb of memory the camera set as above recorded for a maximum 8.9 seconds. With 2 GB of memory usage 70.9 seconds of recording time would have been possible at 100 frames/second. The one disadvantage to this method was the speed of transfer out of the camera to the computer. This was only USB 1.0 speed.

The software package used for the recording and analysing of times was the Citius Imaging, Digital High Speed Video System version 1.2 ©, Citius Imaging Ltd. It allowed for control of the playback speed from 100 frames/s right down to single stepping through the frames. By single stepping it was possible to identify the frames in which the movement began and ended, and these were then captured using the 'save screen image' option within the program which allowed the preservation of both the image and the time mark details. These images were then analysed within the UTHSCA Image Tool program to calculate the maximum angle. The time it took the top plate to achieve its maximum angle was measured by noting the frames at which movement began and was completed, and calculating the time interval based. A sample image is shown in figure 3.18.

There were two ways in which Image Tool could be used to calculate angles. The first method involved using a known distance at the same depth as the angle to be calculated and measuring with Image Tool, the number of pixels in this length. Then by using these two measurements and measuring the height moved by one end of the top plate it was possible to calculate the angle achieved. The other method was to use image tool to calculate the angle directly with the aid of Pythagoras' Theorem, taking the distance between the universal joint connections on the top of the board as the hypotenuse.

Angles calculated in this way were accurate to 1/100 degree. This second option was used for this work.

Figure 3.18 UTHSCA Image Tool image analysis software

Time (seconds)	Pressure (MPa)	Angle (degrees)
0.25	0.2	10.14
0.25	0.5	12.04
0.25	0.8	10.25
0.4	0.2	14.34
0.4	0.5	15.75
0.4	0.8	15.59
0.5	0.2	14.23
0.5	0.5	16.57
0.5	0.8	17.16

Table 3.8 Average angles achieved with an unloaded plate and different pressure and time combinations

Table 3.8 shows the angles achieved experimentally using different tilting times and pressures in a no additional load situation i.e. no one standing on the top plate. It shows the angle achieved by the top plate as being 17.16° as compared to the theoretical 18.41 and the desired 15°. It was observed that with periods of 0.5 seconds that the top plate achieved maximum angle possible within this.

Figure 3.19 shows the average angles achieved by the top plate in an unloaded situation for three different piston supply pressures, 0.2MPa, 0.5MPa and 0.8MPa all the following figures in this chapter detail the balance platform characteristics at these three pressures. Supply pressure to the pistons was allowed through for a period of 0.4 seconds for the lifting phase and 0.4 seconds for the falling phase for all of these situations. Figure 3.20 shows the average angles achieved by the top plate in a loaded situation for these three pressures. The load used was a male volunteer of average weight. These figures were derived experimentally using the high speed camera mentioned above and by examining the frames from these videos with the UTHSCA software also mentioned earlier in this section.

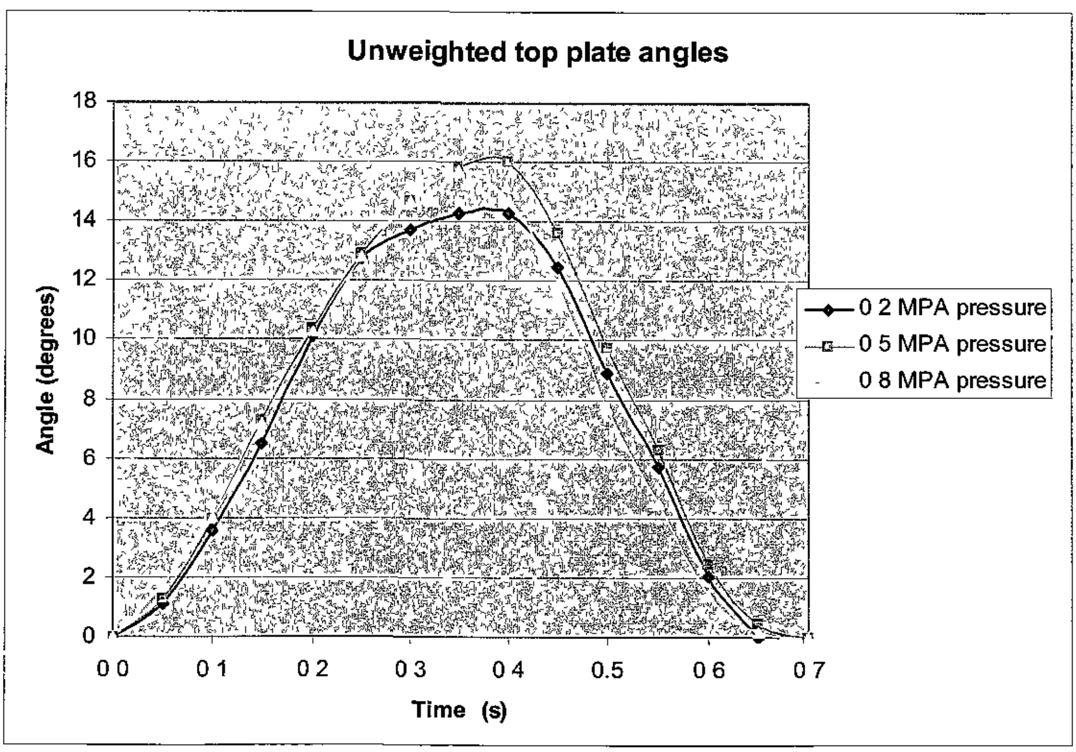

Figure 3.19 Maximum angles achieved for three pressures at 0.4 seconds time no loading

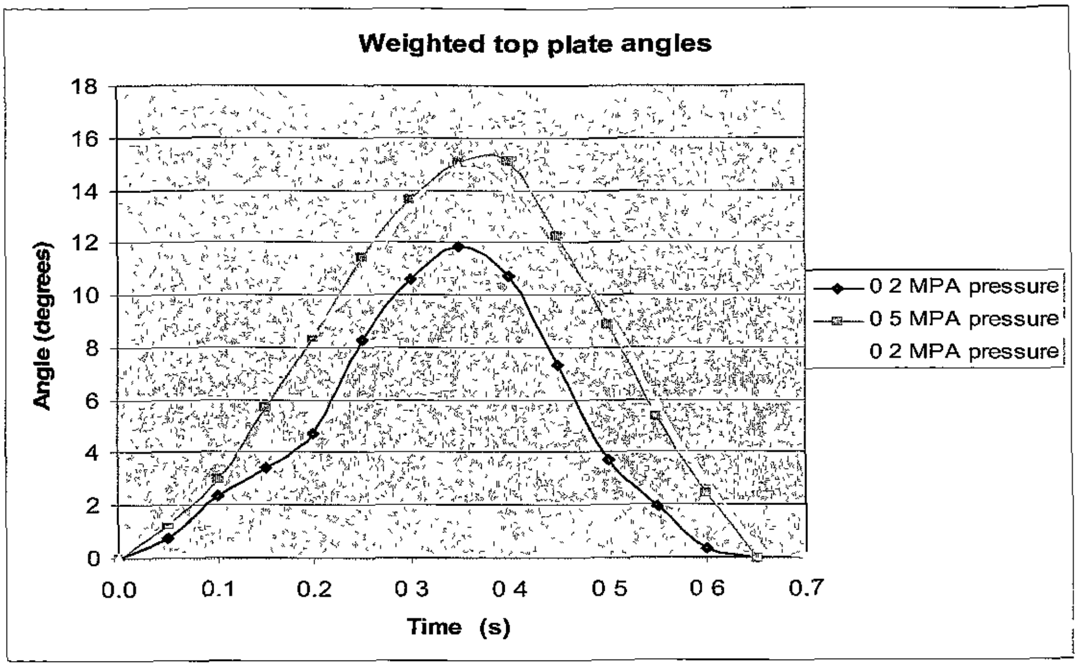

Figure 3.20 Maximum angles achieved for three pressures at 0.4 seconds time with volunteer standing on top plate

As can be seen in the above graphs the added weight of the test subject did have an effect on the angles achieved by the top plate. With the weight of an approximately 81 kg volunteer, there is a noticeable difference in maximum angle, three degrees, achieved when comparing 0.2MPa to 0.5MPa or 0.8MPa as can be seen in figure 3.20. While lead screws or linear motors could have been used to create the movement those with the necessary power were priced at €2000 or more per actuator and four would have been needed. In this as in the other graphs shown below figures 3.21 to 3.24, 0.5 and 0.8MPa pressure results in approximately the same results. A pressure however of 0.2 MPa produced lower angles. The maximum angle achieved between weighted and unweighted results drops by one degree at 0.5 and 0.8MPa and by three degrees at 0.2MPa. This is a significant difference when the maximum angle achieved in an unloaded situation was 14 degrees and when loaded with 81kg was 12 degrees as seen in figures 3.19 and 3.20.

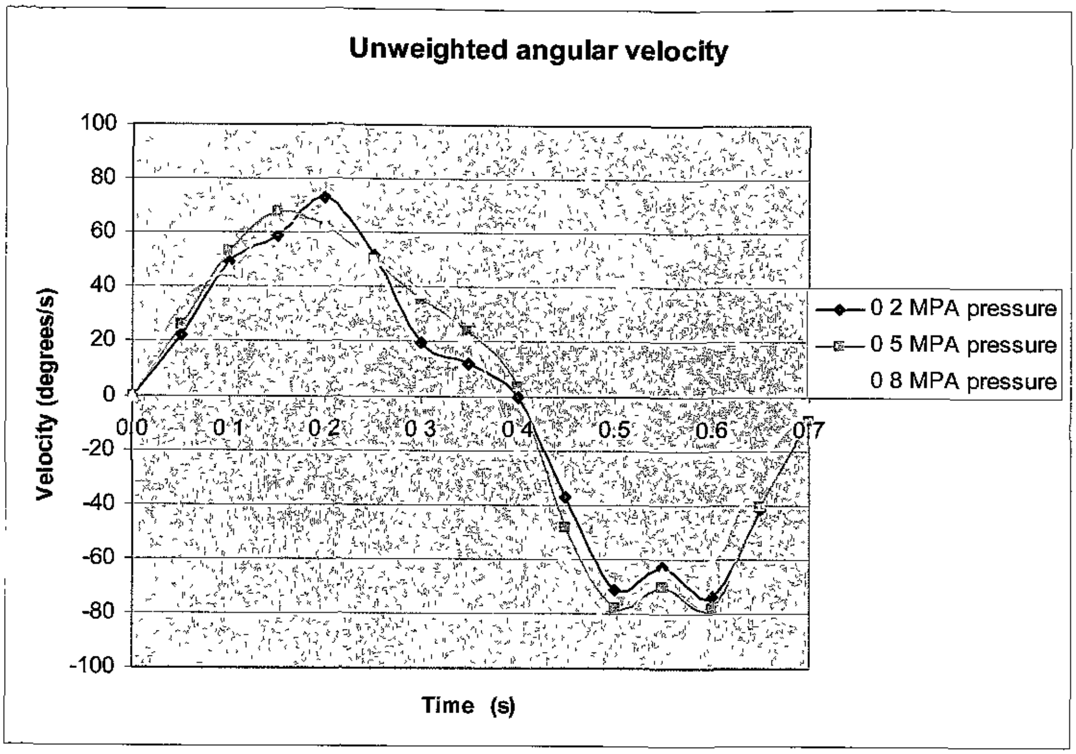

Figure 3.21 Maximum velocities achieved for three pressures at 0.4 seconds time no loading

As can be seen in the above graphs when unweighted all the pressures follow roughly the same line with 0.2MPa showing the most deviance but when the volunteer test subject stood on the top plate the velocity graph was much the same for 0.5 and 0.8MPa but showed significant changes in velocity at 0.2MPa.

Figures 3.23 and 3.24 show the experimentally achieved acceleration values for an unloaded condition on the balance platform and when the 80kg volunteer test subject was standing on the top plate.

As with the results shown in figures 3.21 and 3.22, 0.5 and 0.8MPa show roughly the same results with 0.2 MPa (2 bar) deviating from this most markedly with the added weight of the volunteer.

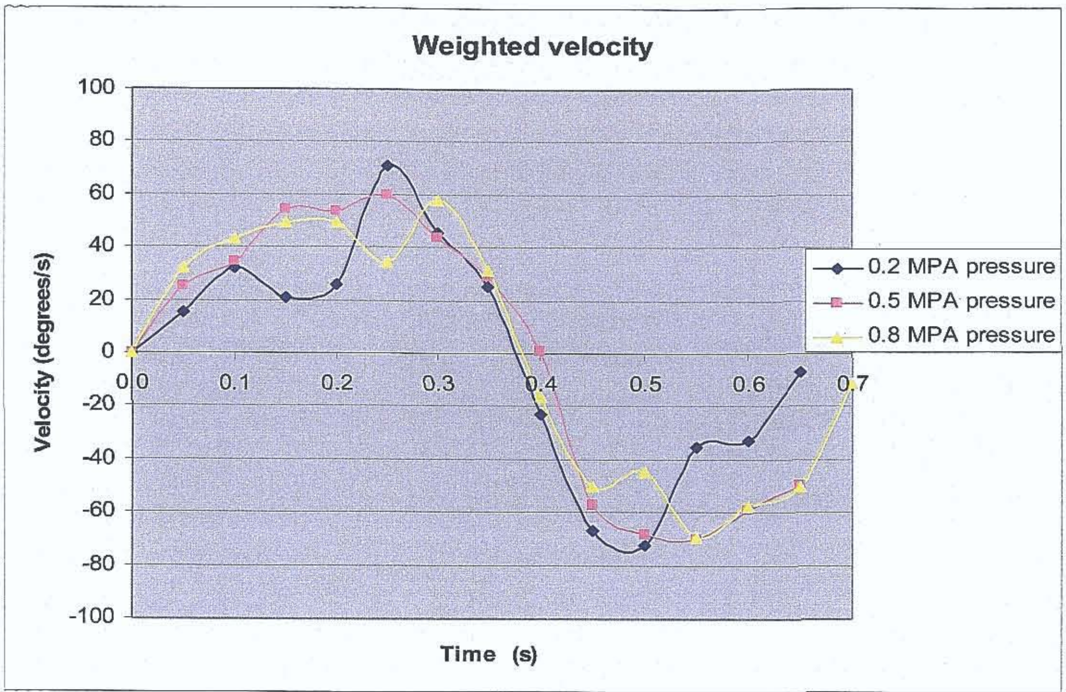

Figure 3.22 Maximum velocities achieved for three pressures at 0.4 seconds time with volunteer standing on top plate

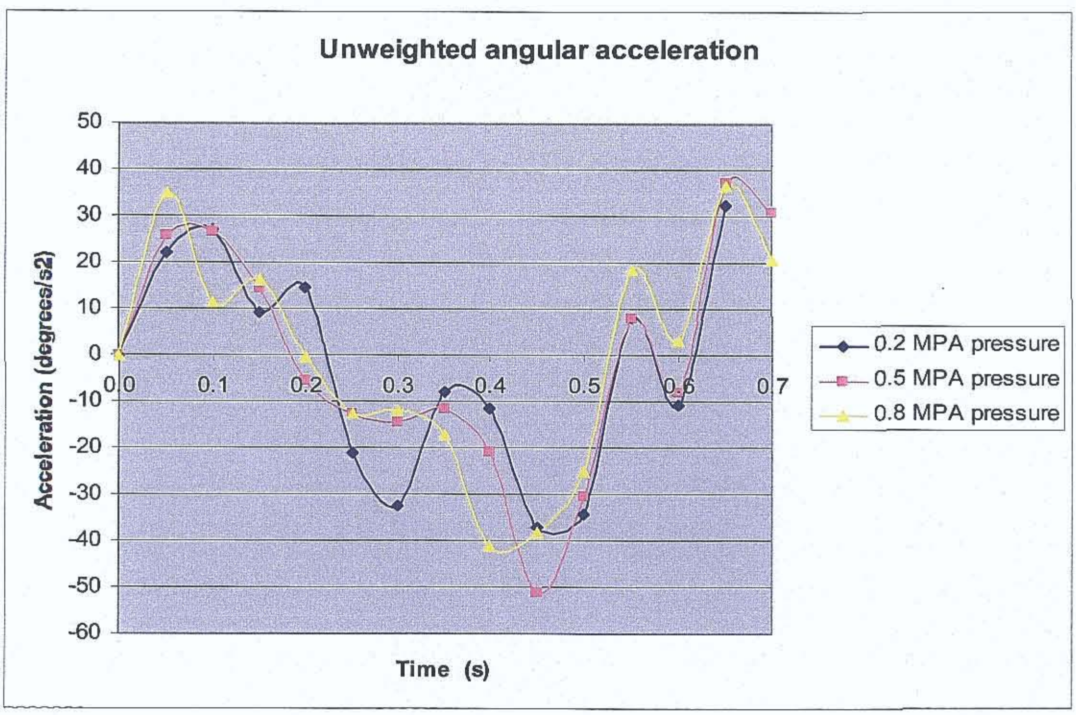

Figure 3.23 Maximum accelerations achieved for three pressures at 0.4 seconds time with no additional loading

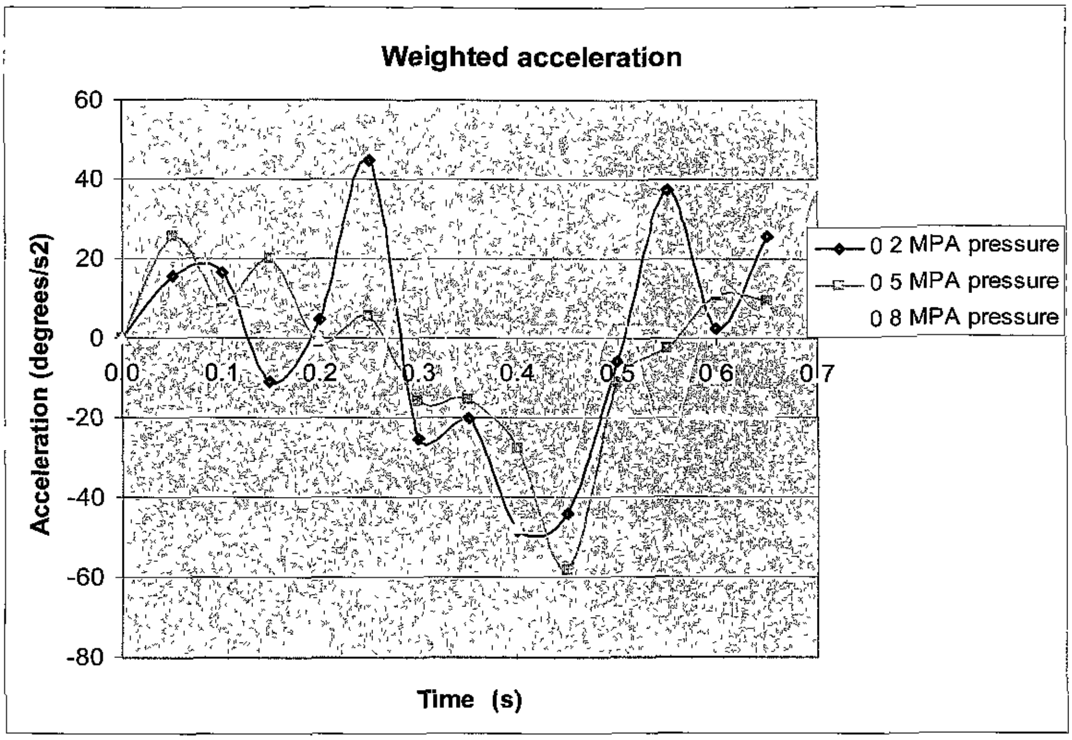

Figure 3.24 Maximum accelerations achieved for three pressures at 0.4 seconds time with volunteer standing on top plate

These groupings were then compared as outlined above and the average result of the five recordings and deviance from this were detailed below in figures 3.25 and 3.26. There is a very high degree of repeatability shown in figures 3.25 and 3.26. These graphs indicate the angle achieved for five repetitions of the same tilting conditions. These graphs highlight the repeatability of the platform at various pressures. With no loading and 0.2MPa of pressure this is shown to be 0.23 degrees of variation. With 0.8MPa and a volunteer there was 0.12 degrees of variation except in the final instance which brought the variance to 0.55 degrees. In the recording of these movements there was a rise time of 0.4 seconds and a two minute gap between measurements to allow the subject more than ample time to ready himself for the next tilting. This length of time between recordings drained the compressor's tank somewhat and this is probably a contributing factor to the lower angles shown in the last readings of figures 3.25 and 3.26. At this point the compressor tank was nearing the cutoff point when it would activate again to bring pressure back from about 0.65-0.7 MPa to 0.8 MPa.

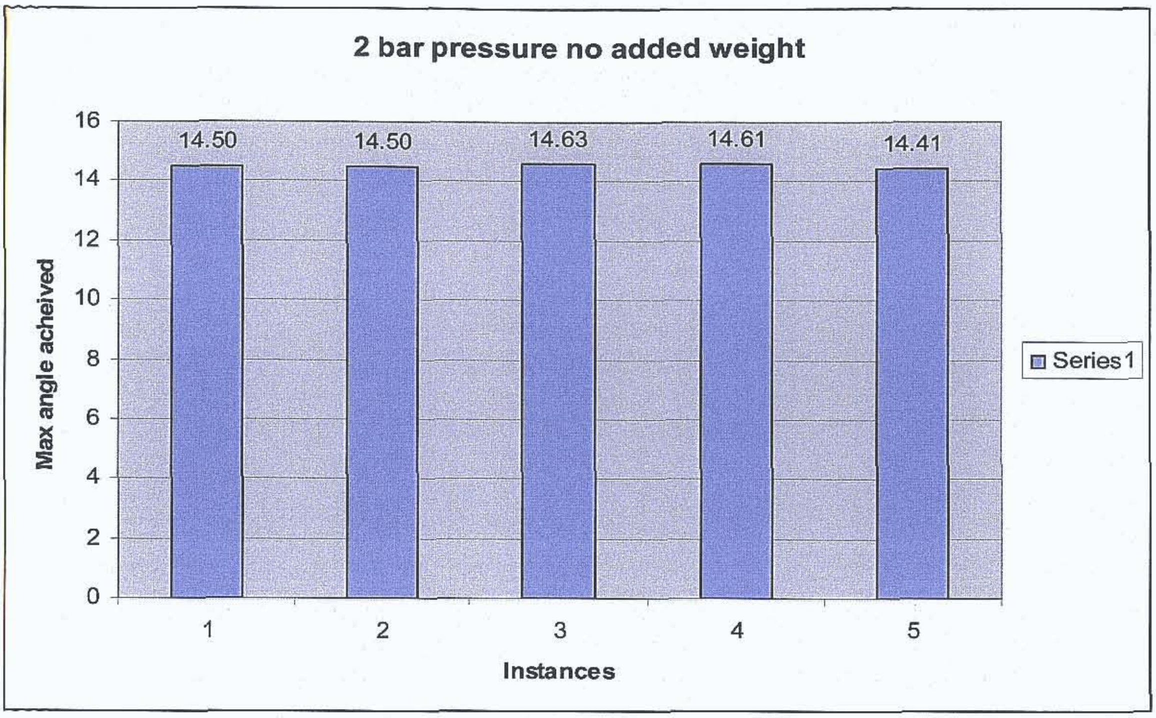

Figure 3.25 Variations in angle achieved at 0.2MPa with no loading

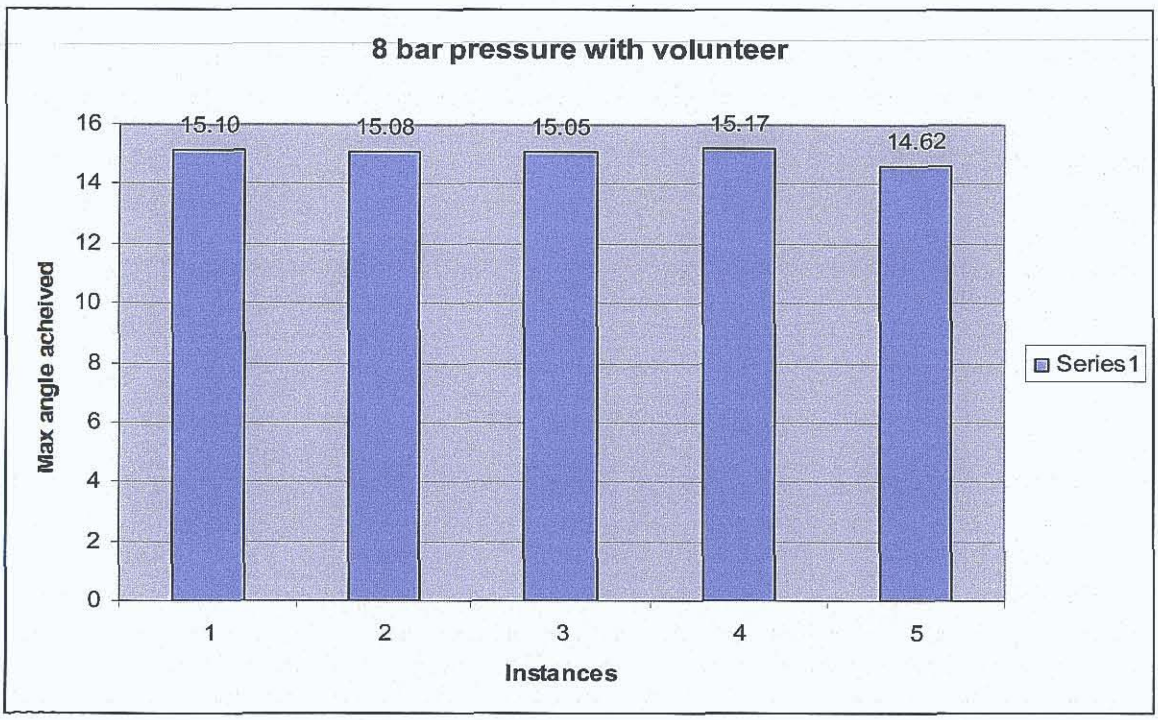

Figure 3.26 Variations in angle achieved at 0.8MPa
with a volunteer standing on top plate

Chapter 4

Human performance trials

4.1 Overview

In many population sub-groups (e.g. elderly, athletes with lower limb joint injuries, and patients with various neuromuscular diseases) it would be beneficial to analyse levels of balance in order either to determine if an appropriate intervention is required or to examine the efficiency of an intervention itself. An effective analysis of balance requires the measurement to be repeatable; that is the balance score would be the same however many times the person was assessed (provided there was no actual change in balance capacity). However, a barrier to repeatability is the 'novelty' of the assessment. With multiple analyses over time a change in balance capacity may be indicated by an increase in balance score when in fact an actual change in balance may not have occurred and the subject may simply have 'learnt' the novel test. This study aimed to determine the average number of measurement sessions required to familiarise subjects with the test and thereby produce repeatable results. Specifically the study examined the point after which significant changes in balance could no longer be said to be due to a learning effect. Identification of this point would allow clinicians to administer an appropriate number of familiarisation sessions (if any) for subjects, beyond which changes in a balance score would reflect actual changes in balance capacity.

4.2 Methods

4.2.1 Subjects

A mixed gender test group of fourteen subjects, two women and twelve men were used. The details for the various test subjects are noted below in table 4.1, their names were withheld for confidentiality purposes.

Each subject was given two forms, a plain language form and an informed consent form to review and sign before taking part in the study (Appendices B and C, respectively).

Subject Id	Gender	Weight (kg)	Height (cm)	Age	Shoe Size	Dominant Leg
1	M	82	183	24	9.5	R
2	M	76	182	24	11	R
3	M	81	181	22	11	R
4	M	66	174	33	8	R
5	M	76	186	26	11	R
6	M	94	180	32	11	R
7	M	77	180	33	10	R
8	F	66	180	26	8	R
9	M	72	172	25	9	R
10	M	107	180	29	10	R
11	F	64	172	28	6	R
12	M	73	193	26	11 5	R
13	M	71	171	33	8	R
14	M	92	179	29	10	L

Table 4.1 Test subject details

4.2.2 Experimental procedure

Subjects were asked to stand on the platform barefooted to accustom them-selves to standing on the unmoving board. Then they were verbally informed of what the test would consist of having already read this information in detail in the two forms. The tests were split into two halves. The first set of tests consisted of six separate movements of the platform, with the platform tilting down in the direction of the volunteer's dominant leg. The subjects were asked to stand upon their dominant leg while being tilted. Before each tilt of the platform they were given a three second countdown to prepare them selves. They were tilted for a period of 250ms at a supply pressure of 0.2MPa then tilted back to a stable, horizontal starting position. The subjects were asked to maintain their upright stable posture for five seconds after tilting to determine how effectively they could (re-) balance themselves. After this time had elapsed they were allowed to move to a relaxed posture with both feet on the platform and their hands at their sides or on the safety rail, whichever proved to be more comfortable. They were allowed two minutes in this relaxed posture before proceeding with the next platform tilt test.

The second half proceeded identically to the first with the sole exception that the platform tilted either to the side of their dominant or non-dominant leg (left or right), with three movements in either direction but with no indication beforehand of which direction it was going to be. The two sets of trials were undertaken to specifically examine the capacity to balance, both when the subject knew and did not know the direction of perturbation. Both procedures have been used by clinicians.

During the trials it was necessary to examine the subject's balance directly after being perturbed. To do this a 0.5 x 0.4m pressure platform, seen in figure 4.1, (RSscan 3D plate; Belgium) was used in conjunction with dedicated balance assessment software (RSscan Balance 7; Belgium) to examine the capacity of the subject to balance (movement in their centre of pressure, COP) along the x and y axes (anterior-posterior and medial-lateral, respectively). Balance was assessed for the two seconds after the platform became horizontal (stationary) again. The data was sampled at a frequency of 200Hz.

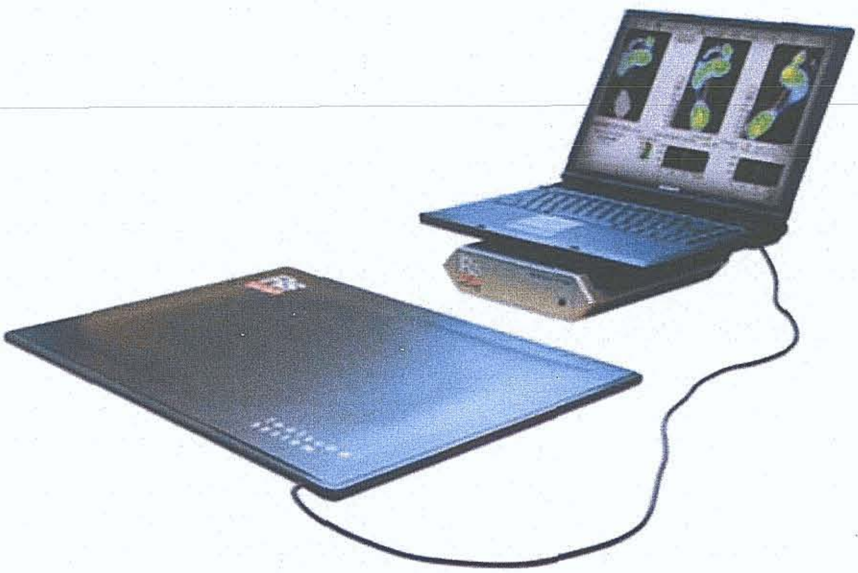

Figure 4.1 RSscan foot plate and control box [70]

Figure 4.2 shows the changes in the centre of pressure over time along the x and y axes from work done in another study figure 4.3 shows similar results from this thesis. Figure 4.2 also demonstrates how the changes in the graph relate to changes in the subject's balance. Figure 4.3 shows the change in the subject's balance (centre of pressure) while maintaining a single legged stance. The blue line in figure 4.3 represents the medio lateral sway of the subject (left to right) and the red line shows the antero posterior sway (front to back). This figure was taken from the trial sessions and shows the results for tilting of one test subject; it was taken using the RSscan. balance assessment software.

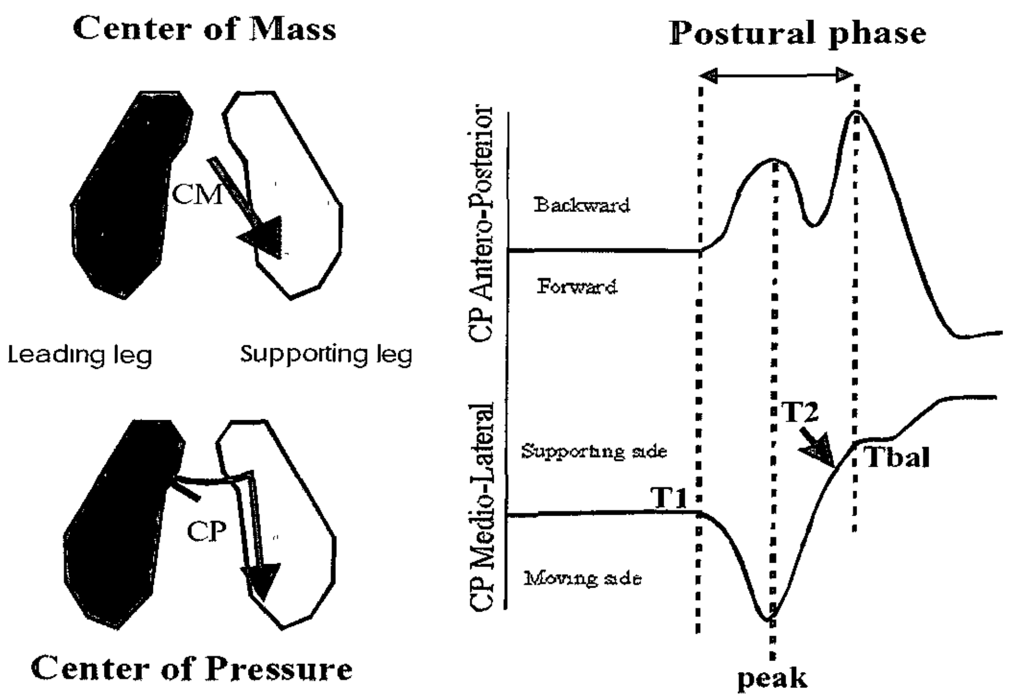

Figure 4.2 Graph of COP movements along the X and Y in another study [71]

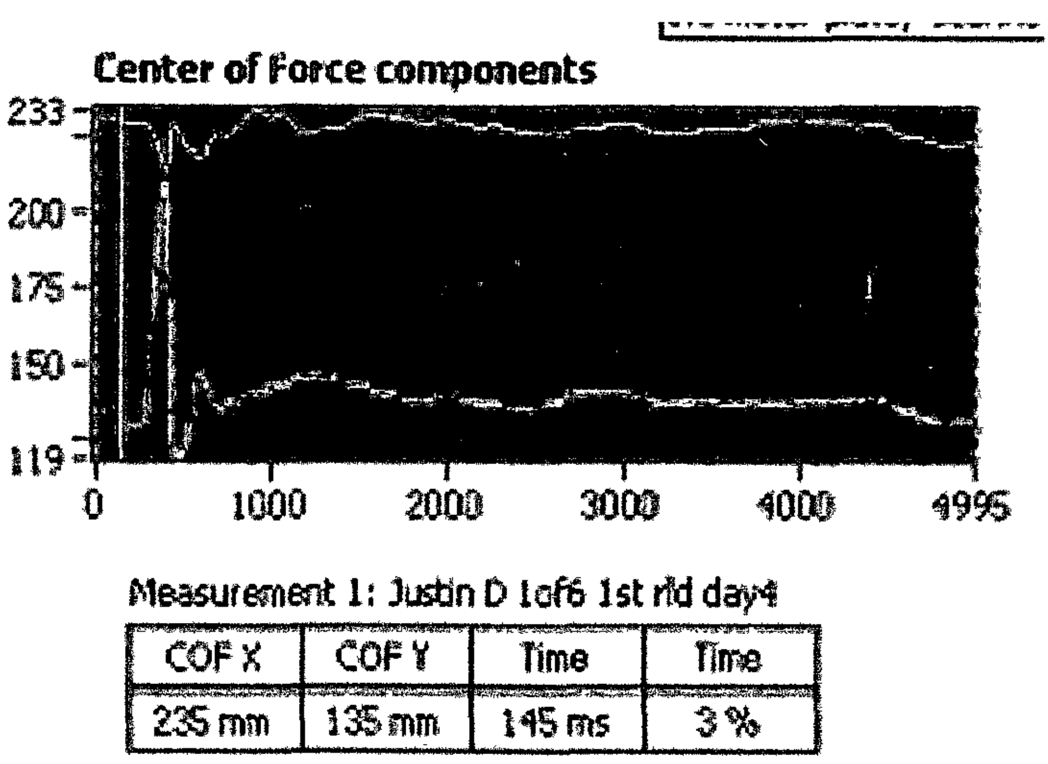

Figure 4.3 Graph of COP movements along the X and Y axes from this thesis

Figure 4.2 and 4.3 show variations in pressure versus time along the medio-lateral, x, and the antero posterior, y, axes.

4.2.3 Data processing

The data from the recorded sessions from each days testing, were exported to individual excel files giving 60 separate files per subject. These 60 files were broken down into five groups, with each group representing the day they were taken on. Each day was then divided into first and second half testing with six tests per half. The six tests in the first half were six tilts in the direction of the subject's dominant leg while standing on their dominant leg. The second half consisted of three tilts to towards their dominant side and three towards their non-dominant side.

Due to the number of subjects and files per subject to be analysed a macro was developed to automate this procedure. It selected the required columns from the exported files and imported them into a pre-prepared Excel spreadsheet A, results from which were exported into spreadsheet B, results from which were then exported into spreadsheet C and finally exported to SPSS for analysis. An excel macro was then developed to open all 840 of these files individually and transform the results into the desired form. The code for this macro can be seen in Appendix F.

4.3 Data Analysis

A number of measures examining changes in COP were determined in relation to both the initial COP (absolute COP) point as well as with reference to the previous COP point (relative COP). The difference between these is illustrated in figure 4.4 A and B. These measures included displacements and velocity of the COP along the x, y axes and the resultant of the two axes. An example of this data is shown in Table 4.2 for one of the test subjects.

Table 4.2 shows just three of the variables measured during the human performance trials. Figure 4.4 shows two of the ways in which the subject's displacement of COP was calculated. Figure 4.4A is showing absolute measurement of displacement of the COP and figure 4.4B showing relative measurement of displacement of the COP.

Code of balance	Average Absolute COF X movement	Average Absolute COF Y movement	Average Resultant COF movement
Aidan C day3 2nd 1of6 left rld	66.00	70.30	107 21
Aidan C day3 2nd 2of6 left rld	54 70	76 60	105 70
Aidan C day3 2nd 3of6 right rld	45.20	66 50	89 52
Aidan C day3 2nd 4of6 right rld	54.90	52 10	88.26
Aidan C day3 2nd 5of6 left rld	73.10	65 00	112.43
Aidan C day3 2nd 6of6 right rld	50 40	52.40	83.48
Average:	51.14	58.17	88.40
Aidan C day4 1st 3of6 - rld	94.60	90.40	145.35
Aidan C day4 1st 4of6 - rld	49.10	55.20	84 71
Aidan C day4 1st 5of6 - rld	43.20	53 60	79 49
Average.	53.53	59.93	91 57

Table 4.2 Sample of results from human performance trials

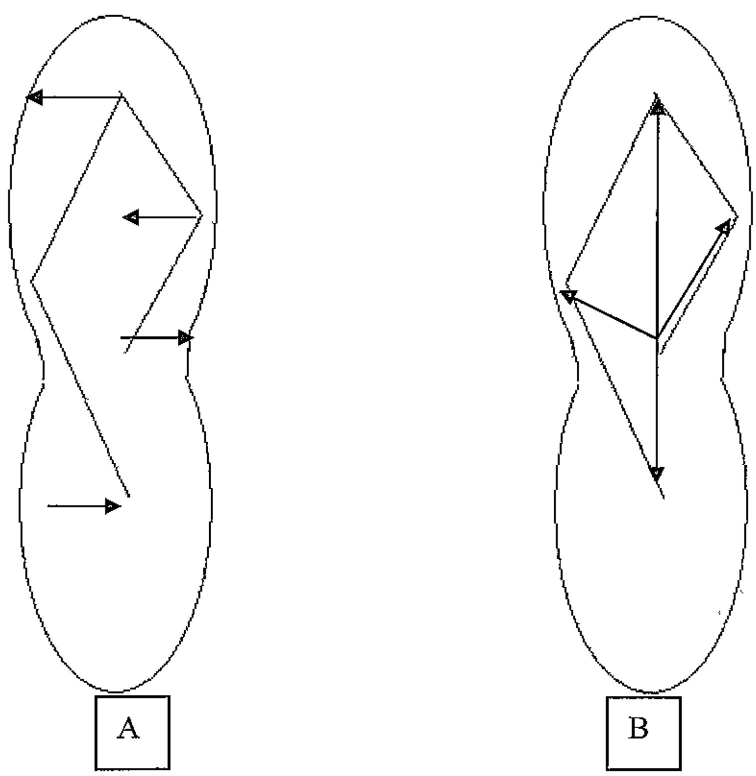

Figure 4.4 Two methods for measuring displacement of COP A) absolute and B) relative

Nine variables, representing movement of the centre of pressure, were used to assess balance (AMTI, Balance Assessment, 2003):

1. Absolute displacement of the centre of pressure (COP) in the x direction.
2. Absolute displacement of the COP in the y direction.
3. Resultant of the average absolute displacement of the COP
4. Absolute velocity of the COP in the x direction.
5. Absolute velocity of the COP in the y direction.
6. Resultant absolute velocity of the COP.
7. Absolute displacement of the COP in the x direction relative to the starting COP position
8. Absolute displacement of the COP in the y direction relative to the starting COP position
9. The elliptical area enclosed by one standard deviation in both the x and y axes.

To assess if the nine measures of balance changed over the five days, a repeated measures anova and intra class coefficient (ICC) were used. In all cases, statistical significance was set at $p = 0.05$. .

4.4 Results

For all of the variables tested for the lateral tilting in both the dominant direction when the subjects knew the direction of tilt, and the non-dominant and dominant directions when the subjects did not know which direction the platform would tilt, there was no significant difference across days, see table 4.3. Although some of the variables were close to significance, non achieved statistical significance. This indicates that the process employed to measure balance is repeatable with no discerning learning effect, and that subjects can be assessed using one test day only, with no familiarity session required. The consistency in results not only reflects the balance test but also the consistency in movement of the balance platform.

Variable Name	F Value	P Value
Absolute displacement of the centre of pressure (COP) in the x direction, dominant side	0.005	0 946
Absolute velocity of the COP in the x direction. dominant side	0 7	0.933
Absolute velocity of the COP in the x direction. dominant and non dominant side	0 7	0.933
Absolute velocity of the COP in the y direction dominant side	0 7	0.933
1. Absolute displacement of the COP in the x direction relative to the starting COP position dominant and non dominant side	0 016	0.902
The elliptical area enclosed by one standard deviation in both the x and y axes dominant side	3.351	0.9
Resultant of the average absolute displacement of the COP dominant side	0.163	0 693
Resultant of the average absolute displacement of the COP dominant and non dominant side	4.036	0.66
1. Absolute displacement of the COP in the y direction relative to the starting COP position dominant side	4.083	0 64
Absolute displacement of the COP in the y direction. dominant side	0.233	0.638
The elliptical area enclosed by one standard deviation in both the x and y axes dominant and non dominant side	1.025	0 33
1. Absolute displacement of the COP in the y direction relative to the starting COP position dominant and non dominant side	1 361	0 264
1. Absolute displacement of the COP in the x direction relative to the starting COP position dominant side	1.77	0.206
Absolute displacement of the centre of pressure (COP) in the x direction dominant and non dominant side	2 328	0.151
Resultant absolute velocity of the COP dominant and non dominant side	4 036	0.066
Absolute displacement of the COP in the y direction. dominant and non dominant side	4 071	0.065
Absolute velocity of the COP in the y direction dominant and non dominant side	4 071	0 065
Resultant absolute velocity of the COP dominant side	4.071	0.065

Table 4.3 Statistical analyses for the repeatability of balance measures

Tables 4.4 and 4.5 show the postural sway for the 14 volunteers recorded during these trials for both the dominant side testing and the dominant and non-dominant side testing

ID	A_1	A_2	A_3	A_4	A_5
1	0.067339	0.518733	0.168979	0.160015	0.203638
2	0.223776	0.305361	0.214098	0.089878	0.165878
3	0.80532	0.401618	0.328055	0.305129	0.207845
4	0.282238	0.212181	0.304628	0.382112	0.235349
5	0.120321	0.364327	0.170096	0.174081	0.258304
6	0.46368	0.385584	0.255303	0.370302	0.209378
7	1.031614	0.157494	0.334211	0.092704	0.221784
8	0.351467	0.477759	1.323554	0.779788	0.475517
9	0.580499	0.499594	0.410082	0.165371	0.348125
10	0.067607	0.073206	0.082629	0.112674	0.125362
11	0.698934	0.23151	0.275507	0.687841	0.384086
12	0.499162	0.882863	0.546806	0.37228	0.561602
13	0.493563	4.184874	0.294698	0.270974	0.24289
14	0.121098	0.192915	0.141624	0.165397	0.260267

Table 4.4 The elliptical area enclosed by one standard deviation in both the x and y axes dominant side

ID	A_1	A_2	A_3	A_4	A_5
1	0.036537	0.206456	0.147041	0.186606	0.220657
2	0.380645	0.265284	0.188014	0.219153	0.252451
3	0.485959	0.48458	0.361329	0.703593	0.318589
4	0.489838	0.440514	0.265201	0.383818	0.72713
5	0.107998	0.281347	0.28566	0.267243	0.29321
6	0.287934	0.265958	0.470193	0.294171	0.422385
7	0.407249	0.267103	0.223463	0.202675	0.16573
8	0.77748	0.514387	0.4665	0.741303	0.614908
9	0.285015	0.383005	0.267872	0.135992	0.388579
10	0.101062	0.138472	0.145252	0.191149	0.1075
11	0.188893	0.417932	0.468517	0.450961	0.429193
12	0.458865	0.409357	0.503325	0.523946	0.778524
13	0.517202	0.300763	0.27415	0.284002	0.387349
14	0.140824	0.18578	0.164374	0.171374	0.147904

Table 4.5 The elliptical area enclosed by one standard deviation in both the x and y axes dominant and non dominant side

In tables 4.4 and 4.5 the vertical axis shows the 14 different volunteers and the horizontal axis shows the average of their six recordings for each of the five days. The elliptical area enclosed by one standard deviation shows the area enclosed by 68% of the average movement of the subjects COP. This gives an indication of the different subjects balance levels for each day.

Chapter 5

Discussion and conclusion

5.1 Design validation

This chapter will examine in detail the results from the testing of both of the balance platform designs, the motorised and the pneumatically actuated builds. It will attempt to determine whether or not the design had a positive effect on the tests performed. These two designs will then be compared to evaluate the differences in the two designs. The final section of this chapter will then go on to detail the conclusions drawn from this work and the recommendations for future work.

5.1.1 Examination of results from motorised build

The results from the motorised build have already been shown in Chapter Two. What is to be discussed here are why this design was rejected and what the plans were to complete it before that decision was reached.

This design was rejected on the basis that it supplied an insufficient turning force and was unable to stop consistently at or maintain a stable horizontal position after tilting with a volunteer standing on it. It was originally thought that using all eight pulleys in the system would allow for enough torque to perturb the volunteer. Due to frequent jamming of the cable in the pulleys this had to be reduced to two in practice reducing the torque outputted by this design to 25% of it's intended value.

The motorised design used two DC electric motors as actuators. They provided a board pulling force of 320N before losses, see equation 2.5. The cheapest DC motor capable of providing a sufficient turning force proved to be beyond the budget for this project. The cheapest was priced at €2500 from Campbell Electric Motors (distributors for ABB motors), with two being required for this build. This would have put the cost of actuators, without any control mechanisms, at almost the entire cost of the pneumatic design.

The other fault with this design was the difficulty in applying a braking force to the top plate. Electric motor brakes were available but those priced to be paired with the motors that were investigated were €2000 or more. This cost, the large force required for the motor option and the complexity of the feedback system that would be needed to ensure accurate control made this an unattractive build and so the pneumatic option was used instead.

5.1.2 Examination of results from pneumatic build

This section will analyse the results from chapter three and address issues that relate to the pneumatic build. The pneumatic build was characterised in chapter three in terms of its maximum possible angle, its velocities, accelerations and its repeatability. In this section these details will be examined to determine how the final system compared to its expected capabilities. The system will be examined under a number of criteria namely the maximum angles, velocities and accelerations.

Figure 5.1 illustrates the horizontal deviation of the pistons vertical movement due to the arc that the top plate moves through.

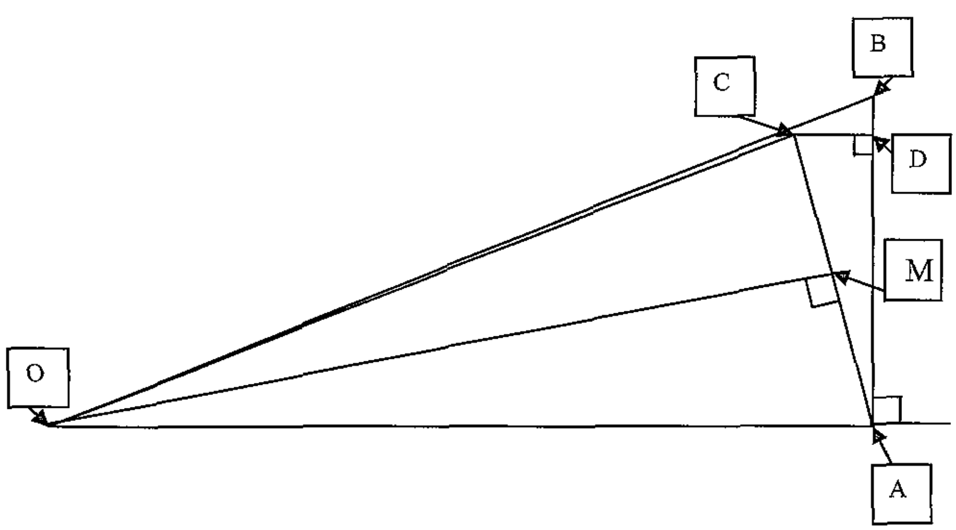

Figure 5.1 Top plate angles and dimensions

OA 0.5(m) Horizontal distance from one piston (fulcrum) to other piston.

OC	0.5(m)	Distance from one piston (fulcrum) to other piston, when raised
AB	0.16(m)	Normal path of piston when unconstrained by top plate
AC	0.16(m)	Actual path of piston when constrained by top plate
AM	0.08m	Midpoint of AC
CD	J(m)	Horizontal deviation from normal piston path
AOB	P°	Maximum angle of top plate
AOC	Q°	Maximum angle possible for top plate with pistons tilting
	R°	Loss of tilting range, difference between AOB and AOC

Some assumptions were made for this particular model of the system shown in figure 5.1. The first being that there was no lateral sliding movement of the pistons relative to the top or base plates i.e. that the bolts holding the piston in place against the top and base plates were held rigidly in place and did not move. This assumption also means that the distances |OA| and |OC| will always remain equal. The second was that the two pistons being held in place and used as fulcrum points for the top plate would stay vertical and not deviate from this to accommodate the motion of the two moving pistons.

Maximum angle theoretically possible AOB, P°

$$P = Sin^{-1}\frac{AB}{OB} = 18.66° \qquad [5.1]$$

Maximum angle occurring

$$Q = \left(Sin^{-1}\frac{AM}{OA}\right) * 2 = 18.41° \qquad [5.2]$$

Loss of tilting range

$$R = P - Q = 0.25° \qquad [5.3]$$

Horizontal deviation from normal piston path accounted for in design.

$$J = \left[Sin\left(90 - \frac{Q}{2}\right)\right] * AC = 0.0256m \; [5.4]$$

The maximum possible horizontal displacement was calculated to be 0.0256m. It was tested that this could be accounted for within the piston shaft rod eye connector joint that attached the piston to the top plate

The first set of calculations compared the maximum possible angle to the maximum achieved in the tests. Equation 3.1 was used to calculate the theoretical maximum angle for lateral tilting (left or right), and this was found to be 18.66°. The experimental analysis found a maximum angle of 17.16°. This showed a discrepancy of 1.5° between the two. One possible explanation may be the limitations on the tilt of the piston which produced a horizontal deviation from its expected path (see Fig. 5.1 where this deviation is represented by the line CD). Another possible contributory factor is the speed at which the tilting motion of the plate was recorded. A higher frame rate might have resulted in a reduction in the apparent discrepancy of the results

In terms of velocity and acceleration the graphs in figures 3.21 to 3.24 showed that a 0.5MPa pressure setting provided a similar performance curve to that of the 0.8MPa setting. The 0.2MPa setting provided much less consistent velocity and acceleration values as can be seen in the results shown in Figure 3.25. The fact that regardless of pressure setting the velocity and acceleration graphs show deceleration prior to reaching the peak angle can be attributed to the trajectory of the piston not being vertical. The piston deviates by 3.57° from a vertical trajectory as measured using Citius Imaging to capture the peak of the movement and UTHSCA Imaging Tool to measure the angle; this can be seen in figure 5.2. However while this affected the expected response for the top plate, it was not significant enough to prevent the project from achieving its aims. The results from equation 5.5 calculated using experimental results support the theoretical calculations of piston deflection in equation 5.4.

H_t = Total piston height when fully extended (mm)

$$Sin(BAC) = \frac{CD}{H_t}$$
$$Sin\ 3.57 = \frac{CD}{320} \qquad (5.5)$$
$$CD = 19.9mm$$

As with the results shown in figures 3.19 and 3.20, 0.5 and 0.8MPa show roughly the same results with 0.2 MPa (2 bar) deviating from this most markedly with the added weight of the volunteer. This indicates the need to use a higher pressure setting while testing subjects than the previously used 0.2MPa. Also in further development work of the balance platform the pressure can be tailored to the weight of the test subject to give more uniform conditions.

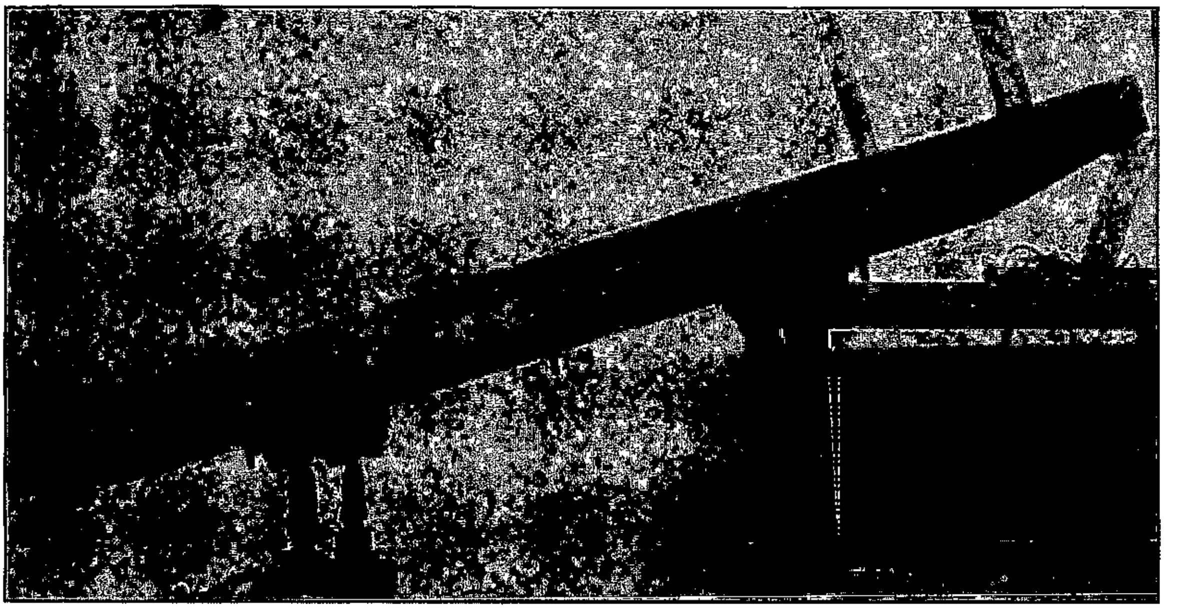

Figure 5.2 Deflection of piston from vertical path

The testing also showed that a scaleable pressure value would be needed when using test subjects with large differences in weight. This can be seen when comparing Figure 3.19 to Figure 3.20. There is a two degree difference in top plate angles. By adjusting the pressure value to the test subject's weight this difference could be eliminated.

Chapter 3 showed that the pneumatic build had ashieved the cirteria for which it was designed. Repeatability of results could have been improved upon by eliminating variance due to changes in pressure level from the compressor i.e. between 0.65MPa and 0.8MPa. Futher testing to fully characterise the system for a range of loadings could also improve system performance by allowing a finer degree of control over the pressures and timings used during testing.

Feedback was also received from qualified medical practicioner, Dr Kieran Moran, on the performance of the balance platform.

Do you feel that the project in its current state allows balance to be assessed?

Yes. The use of the RSscan plate gives very accurate COP measures, which are currently the gold standard for balance assessment. The use of a controllable and repeatable perturbing platform allows accurate and repeatable measures of a patient's capacity to re-balance.

How does it compare to the balance assessment tools already available?

Currently there are only a few (very expensive) devices that allow the patient to be perturbed. Only one of these systems allows the same degree, direction and velocity of perturbation as the developed system and this costs over €100,000. The general approach taken by clinicians/therapists has been to assess balance in relatively static or relatively unrepeatable dynamic conditions, thereby lacking validity and/or repeatability. In addition, such testing does not stress the patients balance capacity enough in order provide a balance assessment sensitive to small changes.

What improvements if any would you like to see?

1. The system could allow the user to 'build' a number of perturbation movements, rather than just the 4 movements currently allowed.
2. A harness could be constructed to allow safe testing of individuals with very poor balance (e.g. elderly)
3. The underlying mechanics could be hidden from the user.

5.1.3 Comparison of pneumatic and motorised designs

This section will compare the experimental results derived from the testing done on the motorised build and on the pneumatic build. Table 5.1 highlights the main areas for comparison of the two builds. In this table the two areas in which the pneumatic build shows no improvement over the motorised build are noise levels and maximum velocity. The maximum loading for the pneumatic design was calculated from the data in table 3.1, for a 0.8 MPa air supply, as follows:

$$\text{Max load} = 6757.07\text{N} / 9.81\text{m/s}^2 = 688 \text{ kg}$$

Characteristic	Motorised build	Pneumatic build
Maximum angle of tilt	+/-18°	17.16°
Tilting axes	1	multi
Maximum loading without operational problems	80kg (found from experimental work, for one tilt)	688kg
Maximum velocity unloaded	1340°/s	187 5°/s
Maximum velocity loaded (80kg volunteer)	0°/s	180°/s
Control System	Basic	Intermediate
Steady horizontal position	No	Yes
Noise	Low	Intermittent noisy
Repeatability	No	High

Table 5.1 Comparison of motorised and pneumatic builds

One basis for comparison was velocities achieved experimentally versus the theoretically calculated values. The theoretical values were calculated in terms of m/s and needed to be converted to degrees/s. This was done using Equation 5.1 described as follows:

OA 0.5(m) Distance from one piston (fulcrum) to other piston, when level

AM 0.08m Midpoint of AC

t time

K angular velocity

$$K = \left[\frac{\left(Sin^{-1} \frac{AM}{OA} \right) * 2}{t} \right] \qquad [5.6]$$

Another basis for comparison was the acceleration values calculated theoretically and experimentally. The acceleration values calculated experimentally were left unchanged whereas the theoretical values were converted to degrees/s for ease of comparison, using Equation 5.2. The maximum acceleration for a given loading and pressure level was used to compare with the theoretical value. This was done because the theoretical values were calculated as end values and not acceleration values over time.

α angular acceleration

a linear acceleration

$$\alpha = \left\{ Sin\left[\frac{\left(a/2\right)}{0.5}\right]\right\} * 2 = 2 * Sin\ a \qquad [5.7]$$

The noise level in the pneumatic build was due to the compressor intermittently activating. When the compressor is not refilling the tank this build is quieter than the motorised build. This could be rectified by using 30MPa air cylinders instead of a compressor and restricting these to 0.05MPa with an adjustable valve between the distribution manifold and the compressor. This has since been implemented during the final year project work in 2006/2007 [** - Daire Geraghty].

The motorised build has a higher maximum velocity when unloaded. When loaded with an 80kg person the motorised build was unable to tilt without the subject leaning in the direction of the tilting to assist the movement. Thus once the builds are compared in a loading situation with a significant weight being used, the pneumatic build was much more capable than the motorised build. The values presented in table 5.1 for the motorised and pneumatic velocities achieved were derived from figures 2.14, 3.21 and 3.22 respectively

The pneumatic build was capable of moving much greater loads, more than the motorised build. This would allow for testing with a much broader range of people. The value given in table 5.1 of 688N is the theoretical maximum load that could be moved using 2 pistons and does not account for the extra force needed to accelerate the load through one tilting in less than one second, this value is taken from table 3.1. The control system for the motorised build allowed directional control. However, the pneumatic build in addition to directional control had the capability of always returning to a horizontal position after tilting and diagonal tilting. Further adjustments that could be made to the control system of the pneumatically actuated design are discussed in

Chapter Six. With its present components the motorised design did not allow for a high level of repeatability of results. The pneumatic design showed a high degree of repeatability (see Figures 3.25 and 3.26).

The pneumatically actuated design represented a significant improvement over the motorised build. Particularly so in the key areas of repeatability, loaded speed of tilting and lastly in allowing for the movement of loads of up to 981N.

Finally the results found in the final year project reports of students Daire Geraghty (2006/2007) and Lisa Foran (2005/2006) can be used to assess the performance of the balance platform created in this work.

5.2 Cost for the pneumatic build

5.2.1 Possible cost reductions

The cost of the system could also be reduced in future builds. After completion of the testing phase some components such as those which facilitated the troubleshooting process could be removed from future designs and the design itself could be altered to take advantage of information gained through the testing phase. Table 5.2 shows the alterations that could be made quickly to reduce the cost of the system. Other cost saving changes that would require further development time were presented in section 5.6

Cost reductions

Description	Saving
Reducing top and base plate size	€25.00
Reducing number of regulators to one	€951 18
Using permanent hose connectors	€341.70
Total	€1,317.88

Table 5.2 Cost reductions table

The electro pneumatic regulators could be replaced with manual pressure regulators or in a more advanced version a single pressure regulator could be placed on the line into the distribution manifold from the compressor. A manual pressure regulator could be adjusted prior to testing of each subject and left at the pre-determined pressure value. The values calculated and shown in Chapter Three could be used to provide a uniform set of conditions for a wide range of test subjects. A more advanced version could make use of an electro pneumatic pressure regulator which would allow for frequent, accurate changes in pressure to provide a more diverse testing. This would be the preferred option and with the changes detailed above the cost of the system would be reduced by €951.18.

The scale of the platform could be reduced to accommodate a more modest 500mm x 500mm top plate size as compared to the current size of 1100mm x 800mm and a base plate size of 750mm x 750mm as compared to 1200mm x 1200mm. This would mean that the top and base plate could be made from a single sheet of 8' x 4' plywood and reduce the cost of this part of the system by €25. This reduced size would also allow a wider choice of material for the plates. The use of materials such as hardened plastic for the plates would now be feasible as their size would no longer be a restricting factor on the use.

Other miscellaneous cost reductions are given below. The 30 Series 522 coupling G3/8 male thread at €10.12 each, quick release connectors, and the 30 Coupling Plug with integral hosetail at €2.53 each was paired for a total of €379.50. These could be replaced with permanent connections. These were selected because during the development of this project the ability to quickly check and change connections was important for trouble shooting purposes. In a finalised design this is no longer an issue. They could be replaced with Brass Euro Coupling Plugs at €1.26 each for a total of €37.80. This would provide a saving of €341.70 over the old design.

The changes described in table 5.2 would represent a total saving of €1317.88 over the old design as outlined in this section. The full cost of the system can be seen in Appendix G

5.3 Conclusion

5.3.1 Achievements

This section details the goals that were achieved during the construction and testing of this project.

- The balance platform was capable of moving through the required ranges of motion, up to 17.16°, along two perpendicular axes, x and y, as shown in table 3.8.
- These ranges of motion were achievable in less than one second with a test subjects that weighed up to 100kg.
- A LabVIEW based GUI was developed to control the functions of the board.
- The LabVIEW based control software interfaced with the user software for the RS Scan force plate.
- The program used to initiate movement of the piston sent a 5V pulse to trigger data collection from the force plate. The software developed during this project interfaced with the commercially available program RSscan.

5.3.2 System Limitations

The following is a list of operations that the balance board cannot perform in its current state.

- Rotation about the third axis (z) is not within this system design.
- Operating like a conventional balance board and allowing the subject to try and maintain their balance on a surface that moves according to changes in their centre of mass. However the training effect of this could be mimicked with gentle random movements, over an extended period of time throughout which the subject would have to try and maintain their balance.
- Varying the instability of the top plate to provide a range of difficulties for those attempting to use it as a balance board as mentioned above.

- Performing translational movements along the x or y axes.

5.3.3 Recommendations

The following section details suggestions that would further enhance the commercial viability and versatility of the project.

A PIC could be used to replace the relay based circuitry. This would provide a more compact control circuit and reduce the build time for this particular section.

A feedback loop control algorithm could be used in conjunction with sensors to provide more accurate measurement and control of the top plate. Various sensor types including sonic and laser sensors would have the necessary sensitivity to improve the control of the top plate beyond that achieved already. This would then eliminate the need to reference a table of pressures and times to compensate for different test subject weights when trying to achieve uniform test conditions.

Load cells could be bought or made to create a simpler and cheaper replacement for the RS Scan pressure plate. Making and calibrating load cells from strain gauges would significantly reduce the cost. Using triangulation the data from the three load cells the centre of pressure of the test subject could be calculated. This would allow the operator to determine the subject's normal postural sway before perturbing them and then use this to determine how long they take to return to this state after being perturbed

The pistons, solenoid valves and the electro-pneumatic regulators are all quite susceptible to damage from debris and water. Using an air filter before the distribution manifold would prevent such foreign matter from entering the system, through the compressor, and damaging parts especially the 5/3 valves and the electro-pneumatic regulators

Quick exhaust ports could be used to speed up the system. They would work by providing a much wider port to vent the air used by the system. The size of the port through which the air vents coupled with the narrow tubing through which it travels to get to the venting port on the 5/3 valve are two of the main bottle necks in the system hindering increased piston speed in the system.

Some reduction in air losses could be achieved through the electro-pneumatic regulators. This might be possible by setting the regulators at 0.5MPa until the pistons are to be moved and then readjusting to the higher pressure.

5.3.4 Medical directives and compliance

This work is currently at the prototype stage and as such is not intended to be compliant with EU medical directives. If this project was to be taken past the prototype stage and to be made into a commercial product it would have to be in compliance with EU Council Directive 93/42/EEC. It would come under the Class I heading as it is non-invasive, is not connected to a Class IIa or higher device, is not intended for storing or channeling bodily liquids or for storing organs, parts of organs or body tissues and with respect with rules 1-18 for classification of medical devices comes under the heading Class I.

5.3.5 Conclusion

From the mathematical and experimental quantization of the system it can be concluded that. the balance platform has a high degree of repeatability when using the same pressure and time settings. It achieved the goals laid out for it in terms of maximum loading, angles, speeds and ability to tilt along multiple axes. It triggered the companion foot pressure profile mat software (RSscan) and provided the user with an easy to use GUI interface. Further human trials would be required to determine how much of an effect it can have in balance testing and other related areas.

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Appendix A- Details of the Romberg test

The Romberg Test usually begins with the subject standing in a bilateral stance for 25-30 seconds, then continues with progressively more difficult stances. The testing is stopped when the subject cannot maintain their balance in a particular stance. This is recorded as a positive result with the scoring being determined by the difficulty of the stance.

Some of the more common variants on the basic bilateral stance are a bilateral stance with the arms raised forwards or standing with one leg in front of the other, this is known as a tandem stance, and a unilateral stance [72]. These variants are known as the 'sharpened Romberg-test'. When evaluating subjects with neurological deficits, Clinical Balance Scores, also known as Stabilometry Scores for other tests, are used as the measure of Postural Stability within the patient. These scores are considered positive when one of the tests is not achieved. However it has been demonstrated through studies that on its own the Romberg test is inadequate for the detection of the more minor balance abnormalities that can be the precursors of major neurological balance disorders.

This type of balance assessment has been used in the testing of subjects with an impaired system noting how they reacted to changes in their environment. This indicates how well their whole balance system compensated for reduced abilities of one of their sensory systems – vestibular, somatosensory or visual [73].

Comparisons could be made between neuromuscular control of right and left extremities and overall postural control. The information gathered could then be used to create individual exercise programs to promote rehabilitation or enhanced performance, while guarding against debilitating injuries.

Appendix B - Plain language form

DUBLIN CITY UNIVERSITY
RESEARCH - INFORMED CONSENT FORM
School of Mechanical & Manufacturing Engineering

Investigators. John Considine B Eng., Dr Dermot Brabazon and Dr Kieran Moran

Research Study Title: Design of a stance balance analysis & training system

Working Title: The effect on balance of familiarization with balance equipment.

Plain Language Statement

For this study you will be required to attempt to maintain your balance while standing upon the balance platform.

- The subject will remove their shoes and socks and stand upon the balance platform.
- The subject will then be given 3 or more practice runs to familiarise themselves with the movement of the platform. Once they are comfortable with this actual testing will begin.
- They will then be asked to stand one legged (their dominant leg) on the platform with hands on their hips, they will be requested to keep their hands on their hips until instructed to move them.
- The platform will then be tilted 6 times in the direction of their dominant leg.
- There will be 45 seconds recovery time in between each tilting, during which time they will be informed when they can use hands or their other foot to help maintain balance and when they must return to the one legged stance in time for the next tilting.
- After these 6 movements they will then repeat the above procedure but this time with the movements being randomised.
- This will conclude on session of which there are 5 in total to be completed.

If you have any further questions please feel free to email them to me at
john.considine@mail.dcu.ie
or alternatively phone me at 087-4104127

Appendix C - Informed consent form

DCU

DUBLIN CITY UNIVERSITY
RESEARCH - INFORMED CONSENT FORM
School of Mechanical & Manufacturing Engineering

Investigators: John Considine B.Eng., Dr. Dermot Brabazon and Dr Kieran Moran

Research Study Title: Design of a stance balance analysis & training system

I.
Working Title: The effect on balance of familiarization with balance equipment.

II. Introduction to this study:

In many people it would be beneficial to improve balance or to know their level of balance. To analyze this test groups can perform balance related drills on a balance platform to assess their proficiency in this area and assess which methods provide the most useful results. To do this repeatability of results is essential. This study is aimed at determining the average number of sessions it takes you the volunteer to become familiar with the movements involved. That is how long before your ability to maintain balance while on an unstable surface stops improving significantly. Thus changes in balance after this point can be said to no longer be due to a learning effect. To do this you will stand upon a laterally tilting balance platform and attempt to maintain an upright posture during and after .

III. I am being asked to participate in this research study. The study has the following purposes:

a) To determine how many sessions it takes before you familiarize yourself with the balance platform.

b) To see is there a difference in results between random and fixed movements

IV. Confirmation of particular requirements as highlighted in the Plain Language *Statement:*

Please complete the following (Circle Yes or No for each question)
Have you read or had read to you the Plain Language Statement
Yes/No
Do you understand the information provided?
Yes/No
Have you had an opportunity to ask questions and discuss this study?
Yes/No
Have you received satisfactory answers to all your questions?
Yes/No

ı

IV. This research study will take place at the:
XB25, School of Health and Human Performance, Dublin City University

V. This is what will happen during the research study:

1. I will be asked to visit XB25 daily for 5 days. I will be required to refrain from strenuous physical activity 24hrs prior to the final visit in week 5.

2. These sessions will last 20 minutes and during which the subject will be asked to stand on the balance platform and maintain their balance in a one legged stance, on their dominant leg while it is tilted. There will be six movements in a fixed direction and six movements in a random direction. Before each of these movements the subject will be given three practice attempts, or more if they are not fully comfortable with this after three attempts If you are right leg dominant the six fixed movements will be to the right and vice versa for left legged participants. The six random movements will consist of three to the right and three to the left but the order of this will be randomized

3. Your balance will be assessed by means of a pressure plate that you will stand upon while being tilted

VI. Sometimes there are side effects from performing unaccustomed exercises. These side effects are often called risks, and for this project, the risks are:

I may experience some muscle soreness in my legs in the days following the familiarization sessions However, this soreness is normal after exercise and usually peaks after 1-2 days and will usually be gone in 4 days.

VII. There may be benefits from my participation in this study. These are:

1. I will be informed of what my level of balance is.

No other benefits have been promised to me.

VIII. My confidentiality will be guarded:

Dublin City University will protect all the information about me and my part in this study within the limitations of the law. My identity or personal information, will not be revealed, published or used in future studies and all data will be destroyed five years after collection. The study findings will form the basis for preparation of a postgraduate thesis, academic publications, conference papers and other scientific publications.

IX. If I have questions about the research project, I am free to call:

Dr. Kieran Moran at telephone no · 01 7008011

X. Taking part in this study is my decision If I do agree to take part in the study, I may withdraw at any point There will be no penalty if I withdraw before I have completed all stages of the study. However, once I have completed the study I will not be allowed to have my personal information and results removed from the database.

XI. Signature:

I have read and understood the information in this form My questions and concerns have been answered by the researchers, and I have a copy of this consent form Therefore, I consent to take part in this research project entitled·

Signed: ______________________________

Name in block capitols: ______________________________

Witness: ______________________________

Date: ______________________________

This Informed Consent form was officially approved by the DCU Research Ethics Committee on.

____/____/____

Official DCU Stamp

Appendix D - Electrical and software trouble shooting routine

Below is an outline of the troubleshooting procedure used to determine the cause of problems with the platform after the initial setup.

Testing of the system was done in stages to step through all of the different components separately and methodically. Once LabVIEW's own internal checks had stated the program was functional, the outputs to the breakout box were tested. A digital voltage meter (DVM) was next used to ascertain that the correct outputs were being triggered.

Next the relays were tested for functionality by connecting them to the terminal blocks on the breakout box and using the Measurement and Automation software to activate them individually, relying on the audible clicking made by relays when operational to determine whether or not a given relay was working. In the interest of safety, all other power sources were off at this point. Further since there was a direct connection between terminal blocks and relays, it could be reliably said that a single digital output would only ever trigger a single relay and cycling separately through the eight digital outputs would produce eight separate "clicks" allowing for rapid testing of the relays.

Once the relays were confirmed as working correctly the solenoid valves were then tested. These also produced a distinct audible click which could be used to quickly ascertain functionality. Only one relay was initially connected to a given solenoid and was capable of activating it. This worked similarly to the relay testing described above but with the PSU on this time to allow the necessary voltage through the active relays to activate the solenoids. The solenoids in turn controlled the 5/3 valves used. These valves allowed for the directional control of the air entering the pistons and are discussed in further detail later in this Chapter.

Finally this procedure was repeated with the compressor also being powered on.

This made it possible to determine whether air was being supplied to the proper pistons and in the correct direction. Once the testing of all four pistons was completed the LabVIEW based control program was used in place of Measurement and Automation to further test the system. The pistons used are discussed in further detail later in this chapter.

Appendix E - User manual for balance platform

- Check both plugs are connected at wall sockets and on
- Switch on PC, green button on the front
- Login to pc using the username: ssh, there is no password needed with this account
- Open up the folder on the desktop marked Control Software
- Click cancel on LabVIEW registration
- Click Ok on LabVIEW
- The control software seen in fig3.7 of this thesis should now be seen on screen.
- Ensure the red button on the compressor shown in fig.2 is up.
- Turn right hand (when facing gauges) dial, on compressor 90° clockwise to pressurise system. See fig.3 RHS.
- Switch on power supply (PSU), large black switch on left hand side of PSU front panel fig.4, ensure voltage reads 24V and current is limited to a maximum of 1.1A.
- Press the rightmost of four buttons on black rectangular part of PSU front panel, the current should now correctly display what is being drawn by the system. Please note this is less than what the system is limited to and cannot be used to assure the current is correctly limited as per the previous step.
- On PC click arrow button in the top left hand corner of program, see fig.1
- Enter 250 in the white panel of program.
- Click on one of the four directional buttons on the program, to move platform in the indicated direction.
- When finished click on the button marked stop on the program.
- Switch off the power supply by pressing the), large black switch on left hand side of PSU front panel fig.4.
- Turn the dial on the compressor 90° counter clockwise.

- Press the red button on the compressor, this was shown in fig.2 if no more air is wanted, if you need to refill the tank this button can be left up and so long as there is less than 7 bar pressure in the tank, it will work until it reaches capacity

Appendix F – Macro for Human Performance Trials Results

```
Sub MainGrab()
'
' MainGrab Macro
' Macro recorded 6/25/2006 by Marcy O'Neill
'
   Dim Root_Folder As String
   Dim Patient_Folder As String
   Dim Patient_File As String
   Dim Patient_Name As Variant
   Dim Patient_Names(100) As String
   Dim Patient_Count As Integer

   'Patient folders and calculator file
   Folder_Name = "Balance"         'Change this to the  name of the folder
containing the files
   Root_Folder = "C:\" & Folder_Name   'Change this to the path of the folder
containing the files

   Workbooks.Open Filename:=Root_Folder & "\Master - Stability
data_dynamic_JOHN.xls"

   'Look for patient folders in root folder and add them to array list.
   Patient_Count = 0
   MyPath = Root_Folder & "\"   ' Set the path.
   Patient_Name = Dir(MyPath, vbDirectory)   ' Retrieve the first entry.
   Do While Patient_Name <> ""   ' Start the loop, move between folders.
      ' Ignore the current directory and the encompassing directory.
      If Patient_Name <> "." And Patient_Name <> ".." Then
         ' Use bitwise comparison to make sure Patient_Name is a directory.
         If (GetAttr(MyPath & Patient_Name) And vbDirectory) = vbDirectory Then
            Patient_Names(Patient_Count) = Patient_Name
            Patient_Count = Patient_Count + 1
         End If
      End If
      Patient_Name = Dir   ' Retrieve the next folder
   Loop

   'Process each name on list
   For Each Patient_Name In Patient_Names
      If Patient_Name <> "" Then
         'Prompt for patient name or go through all folders alphabetically.
         Patient_Folder = Root_Folder & "\" & Patient_Name

         ' Look intp the patient folders for individual files
```

```
        MySubPath = Patient_Folder & "\"    ' Set the path.
        Patient_File = Dir(MySubPath & Patient_Name & "*.xls")    ' Retrieve the
first entry.
        Do While Patient_File <> ""    ' Start the loop.
          Test = Split(Patient_File, " ")
          Field_ID = Left(Test(0), 1) & Test(1) & Right(Test(5), 1)

          ' Open and convert file into excel sheet
           Workbooks.OpenText Filename:= _
              MySubPath & Patient_File, Origin:=932, StartRow:=1,
DataType:=xlDelimited, TextQualifier:= _
              xlDoubleQuote, ConsecutiveDelimiter:=False, Tab:=True,
Semicolon:=False, _
              Comma:=False, Space:=False, Other:=False,
FieldInfo:=Array(Array(1, 1), _
              Array(2, 1), Array(3, 1), Array(4, 1), Array(5, 1), Array(6, 1), Array(7,
1), Array(8, 1), _
              Array(9, 1), Array(10, 1), Array(11, 1), Array(12, 1), Array(13, 1),
Array(14, 1), Array(15 _
              , 1), Array(16, 1), Array(17, 1), Array(18, 1), Array(19, 1), Array(20,
1), Array(21, 1), _
              Array(22, 1), Array(23, 1), Array(24, 1), Array(25, 1), Array(26, 1),
Array(27, 1), Array( _
              28, 1), Array(29, 1), Array(30, 1), Array(31, 1), Array(32, 1),
Array(33, 1), Array(34, 1), _
              Array(35, 1), Array(36, 1), Array(37, 1), Array(38, 1), Array(39, 1)), _
              TrailingMinusNumbers:=True

           Range("A10:D10").Select
           Range(Selection, Selection.End(xlDown)).Copy
           Windows("Master - Stability data_dynamic_JOHN.xls").Activate
           Range("A15").Select
           ActiveSheet.Paste

           Range("H13:AA13").Copy
           Windows("Summary_stability data.xls").Activate
           Sheets("data").Select
           Range("B2").End(xlDown).Offset(1, 0).Activate
           Selection.PasteSpecial Paste:=xlPasteValues
           'GL - ActiveCell.Offset(0, -1).FormulaR1C1 = Field_ID
           ActiveCell.Offset(0, -1).FormulaR1C1 = Test(0) & " " & Test(1) & " " &
Test(5) & " " & Test(3) & " " & Test(2) & " " & Test(6) & " " & Test(4) ' & "|" &
Test(8) & "|" & Test(9) & "|" & Test(10) & "|"
           If Test(2) <> OldTest Then
              ActiveCell.Offset(1, 0) = "This is a test gap"
           If Test(6) = "-" Then
```

```
        ActiveCell.Offset(1, 1) = "=Average(B10:B20)"
      End If
      End If

      'Label the data line (enter some sort of convertion here.)
      Sheets("listing").Select
      Range("A1000").End(xlUp).Offset(1, 0).Activate
      ActiveCell.Value = Field_ID
      ActiveCell.Offset(0, 1).Value = Test(0) & " " & Test(1)
      ActiveCell.Offset(0, 2).Value = Test(2)
      ActiveCell.Offset(0, 3).Value = Test(3)
      ActiveCell.Offset(0, 4).Value = Test(4)
      ActiveCell.Offset(0, 5).Value = Test(5)
      ActiveCell.Offset(0, 6).Value = Test(6)
      ActiveCell.Offset(0, 7).Value = Test(8) & "/" & Test(9) & "/" & Test(10)

      Windows(Patient_File).Close
      Patient_File = Dir    ' Get next entry.
      OldTest = Test(2)
    Loop
  End If
 Next
 Windows("Master - Stability data_dynamic_JOHN.xls").Close
SaveChanges:=False
End Sub
```

Appendix G – System Cost

Costings Sheet

Part Name	Net Price	Quantity	Total Price
Piston 80x160 double acting profile cylinder	€109.53	4	€438.12
Ccompressor 2hp 1.5kW 50l 844rpm	€275.00	1	€275 00
Metalwork 80mm flange mounting	€14.99	4	€59 96
Metalwork 80mm foot mounting	€9.53	4	€38.12
Rodeye connector 80/100 cylinder	€43.00	4	€172 00
Rear swivel for 80mm cylinder	€29.95	2	€59 90
Series 522 coupling G3/8 male thread	€10.12	30	€303.60
Brass bulkhead connector G3/8 inside to G1/2 outside	€4.09	8	€32 72
Distribution manifold	€113 07	1	€113 07
Clear braided PVC hose 3/8"	€29.21	1	€29.21
Paralell Plug G1/2	€1.28	1	€1.28
Brass bulkhead connector G1/4 inside to G3/8 outside	€2.74	1	€2.74
Electro Pneumatic Regulator	€317.06	4	€1,268.24
3/4" thick marine plywood 8'x4'	€75.00	1	€75.00
1" thick marine plywood 8'x4'	€93.99	1	€93.99
24V 2A Power supply	€200.00	1	€200.00
Relay 5VDC (3103493)	€6.03	12	€72.38
Glue, Screws, Bolts, Nuts, Washers, PTFE	€126.75	NA	€126.75
Pnematic Components	€749.03	NA	€749.03
LabVIEW Software	€991.73	1	€1200.00
LabVIEW PCI DAQ card	€578 51	1	€700.00
Pressure plate & RSscan software	€18653 00	1	€22570 00
V.A.T.			€4,475.57
Total			€29,644.44

Appendix H – Biodex Balance System quote

John Considine
DCU
Dublin

<u>Quotation for John Considine</u>

Please find detailed below a quotation for the equipment as discussed:

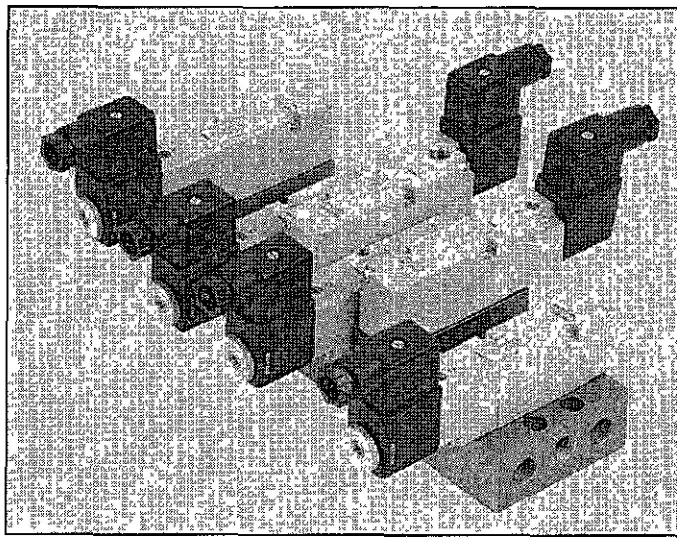
Biodex Balance System – (945-302) Includes printer and printer stand CE certified to medical directive	***€ 9895.00***
VAT (@21%)	***€ 2176.90***
Total to pay	***€12,071.00***

* **All prices include delivery,installation and 1 year warranty**

Appendix I - Datasheets

VENTILER SERIE 70, BASANSLUTNING

Serie 70 ventiler för basanslutning, som endast finns i luft-och elstyrt utförande, är ett utmärkt rent alternativ för applikationer då det är nödvändigt att kunna komma åt ventilerna utan att demontera rören. På dessa sitter ingång, utgång och ytterligare portar på undersidan. Systemet är perfekt balanserat så ventilerna kan monteras i valfritt läge.

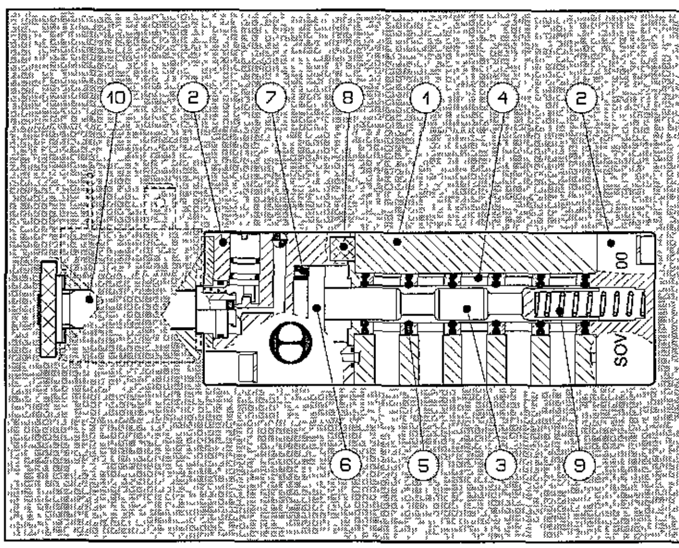


TEKNISKA DATA

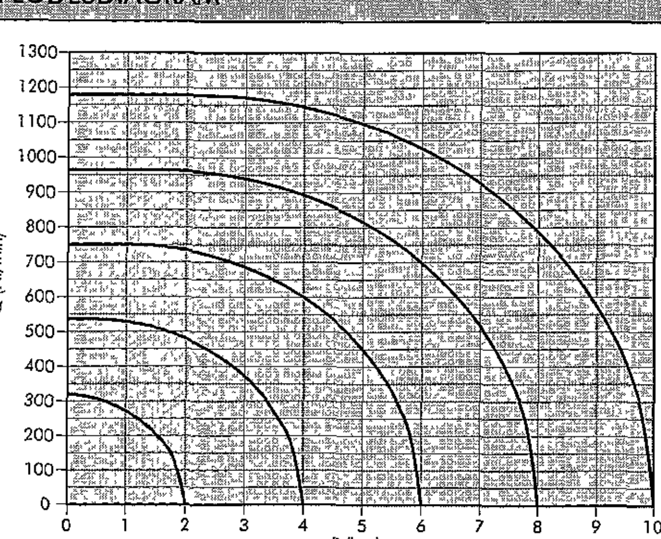
Arbetstryck:	• monostabil	2,5 till 10 bar
	• bistabil	1 till 10 bar
	• extern luftforsörjning	vakuum till 10 bar
Arbetstemperatur		-10°C till +60°C
Min. aktiveringstryck		2,5 bar
Nominell diameter		5 mm
Konduktans C		107,69 Nl/min · bar
Kritiskt värde b		0,29 bar/bar
Flöde vid 6 bar ΔP 0,5 bar		320 Nl/min
Flöde vid 6 bar ΔP 1 bar		450 Nl/min
Max. vridmoment låsmutter spole		1 Nm

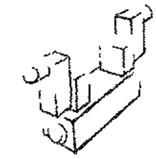
MATERIALSPECIFIKATION

① Ventilkropp: Aluminium
② Pilotventilhus: Hostaform®
③ Slid: Kemiskt förnicklad aluminium
④ Distansplattor: Plast
⑤ Tätningar: NBR
⑥ Kolv: Hostaform®
⑦ Kolvtätning: Polyuretan
⑧ Filter: Sinterbrons
⑨ Fjäder: Specialstål
⑩ Magnetsystem: Ankarrör av mässing, ankare av rostfritt stål

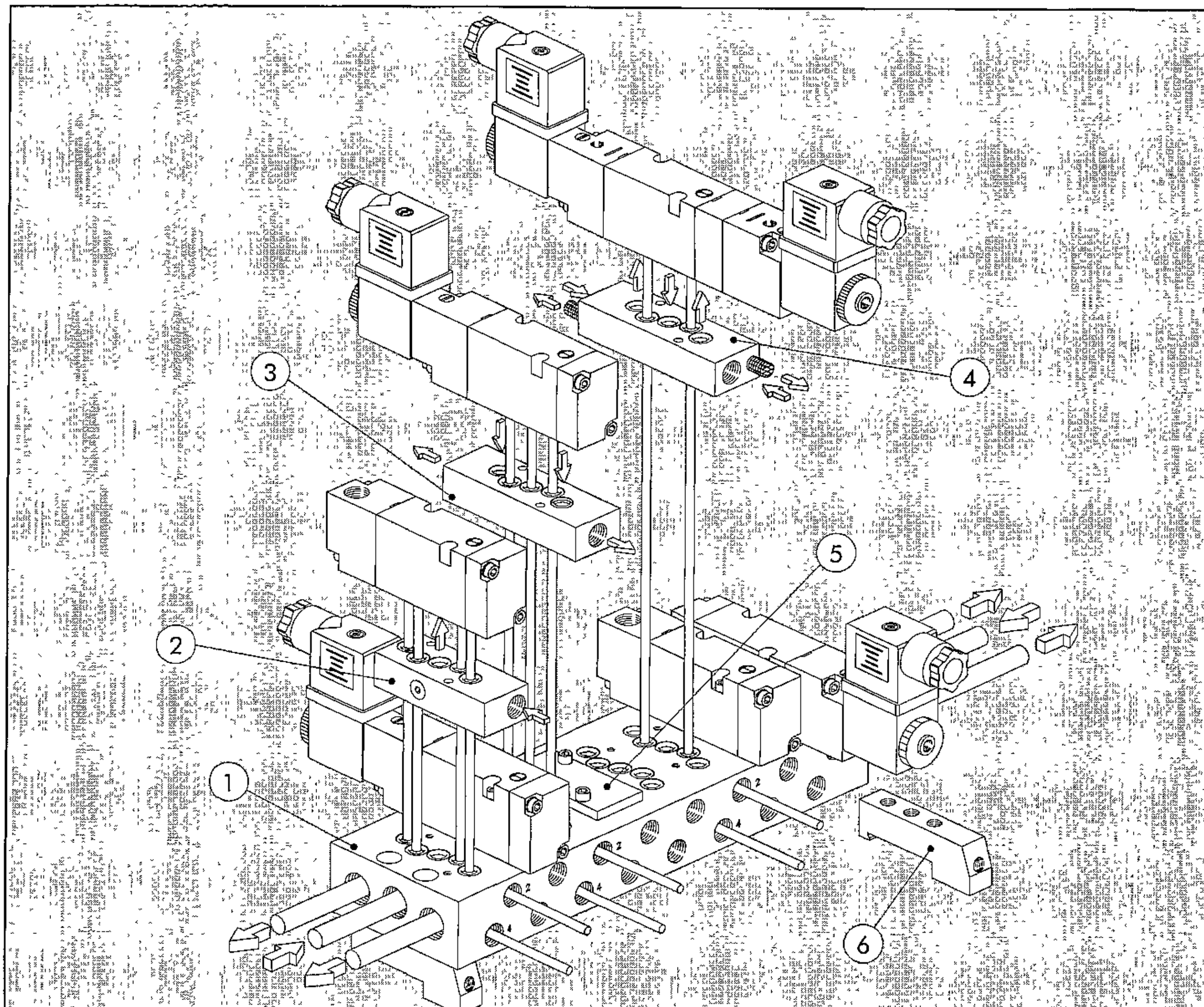


FLÖDESDIAGRAM





MULTI BASPLATTA FÖR VENTILER SERIE 70 MED BASANSLUTNING



Referens	Beskrivning	Artikelnr
①	Basplatta 2 positioner	0223100201
	Basplatta 4 positioner	0223100401
	Basplatta 6 positioner	0223100601
	Basplatta 8 positioner	0223100801
	Basplatta 10 positioner	0223101001
②	Mellanplatta for sep påluftning	0223106301
③	Mellanplatta for sep avluftning	0223106303
④	Mellanplatta for avluftstrypning	0223106302
⑤	Blindplatta	0223106500
⑥	Adapter för omegaskena	0226004600

BESTÄLLNINGSNYCKEL

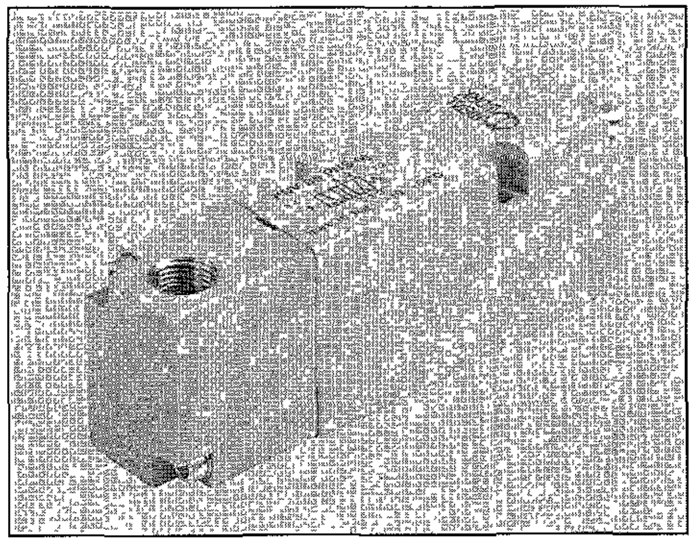
P N V B 5 P N S O O

FAMILJ		ANSL		FUNKTION		AKTIVERING 14		RETUR 12		ANDRA SPECIFIKATIONER	
PNV	luftstyrd	B	1/8" basanslutn.	5	5/2	PN	luftstyrd	S	fjaderretur	OO	5/2
SOV	elstyrd			6	5/3	SO	elstyrd	B	bistabil	CC	stängt mittläge
						SE	elstyrd, extern luftfors	D	differential	OC	öppet mittläge
										PC	trycksatt mittläge

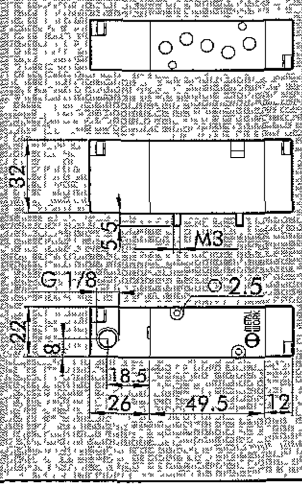
LUFTSTYRDA VENTILER SERIE 70, BASANSLUTNING

TEKNISKA DATA

Arbetstryck	Vakuum – 10 bar
Min. aktiveringstryck	2.5 bar
Arbetstemperatur	-10° – +60°C
Nominell diameter	5 mm
Konduktans C	107.69 Nl/min · bar
Kritiskt värde b	0,29 bar/bar
Flöde vid 6 bar ΔP 0.5 bar	320 Nl/min
Flöde vid 6 bar ΔP 1 bar	450 Nl/min
TRA/TRR monostabil vid 6 bar	6 ms / 15 ms
TRA/TRR bistabil vid 6 bar	7 ms / 7 ms

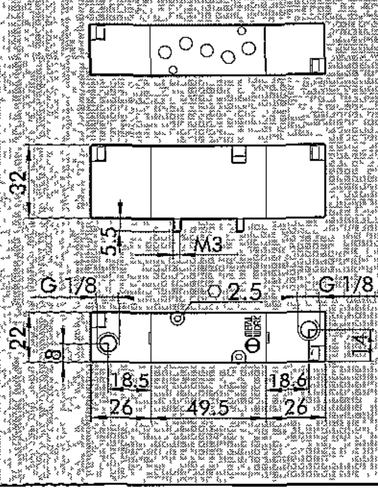


MONOSTABIL 5/2



Symbol	Benämning	Artikelnr	Vikt [g]
	PNV B5 PNS OO	7011011100	125

BISTABIL 5/2



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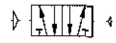
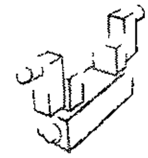
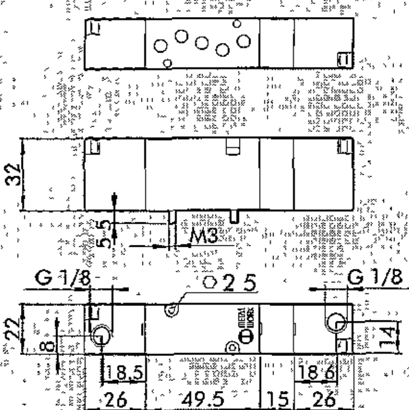
	PNV B5 PND OO	7011011300	142



MONOSTABIL 5/3



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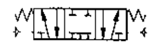
	PNV B6 PNS CC	7011012100	164
	PNV B6 PNS OC	7011012200	164
	PNV B6 PNS PC	7011012300	164

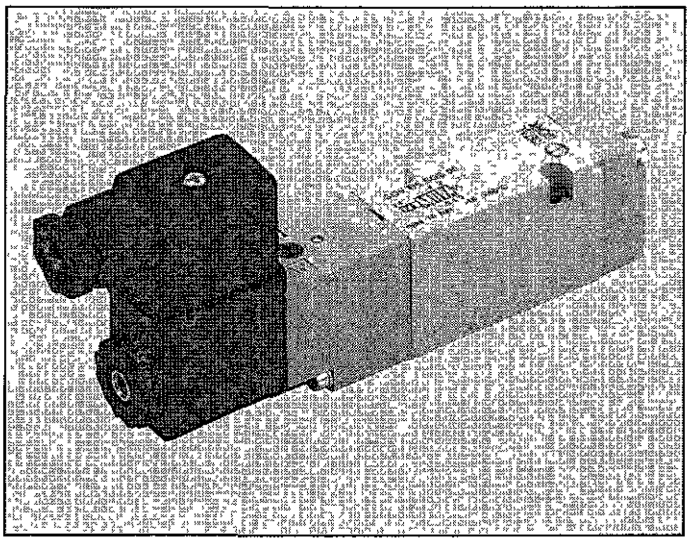
2

NOTERINGAR

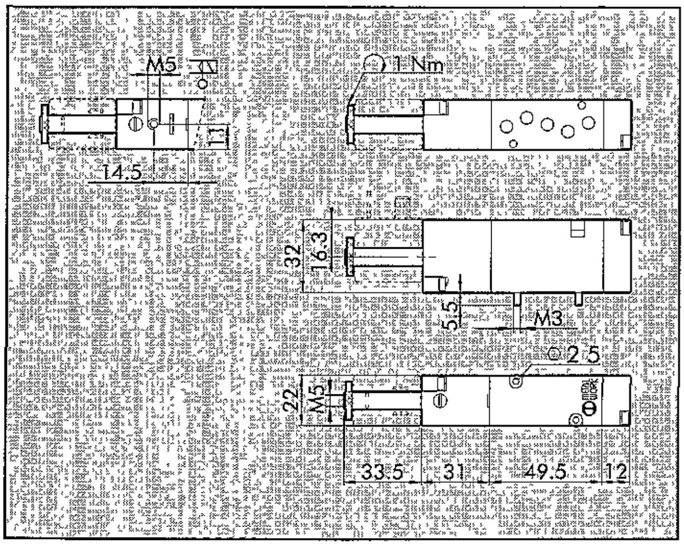
ELSTYRDA VENTILER SERIE 70, BASANSLUTNING

TEKNISKA DATA

Arbets- tryck • monostabil	2 5–10 bar
• bistabil	1÷10 bar
• extern luftfors	vakuum–10 bar
Min aktiveringstryck	2,5 bar
Arbetstemperatur	-10° till 60°C
Nominell diameter	5 mm
Konduktans C	107 69 Nl/min bar
Kritiskt värde b	0,29 bar/bar
Flode vid 6 bar P 0 5 bar	320 Nl/min
Flöde vid 6 bar P 1 bar	450 Nl/min
TRA/TRR monostabil vid 6 bar	15 ms / 35 ms
TRA/TRR bistabil vid 6 bar	20 ms / 20 ms
Tekniska data elkomponenter	
Spänningsutföranden	24VDC; 24VAC; 110VAC, 220 VAC 50/60Hz
Effekt	2 W (DC) 3VA (AC)
Spänningstolerans	-10% – +15%
Isoleringsklass	F 155
Max. vridmoment låsmutter spole	1 Nm

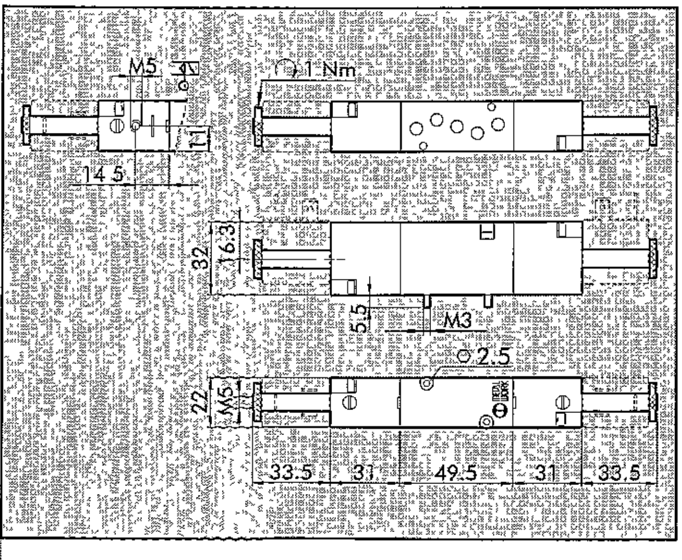


MONOSTABIL 5/2

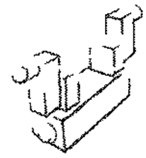


Symbol	Benamning	Artikelnr.	Vikt [g]
	SOV B5 SOS OO	7011021100	142
	SOV B5 SES OO	7011021500	143

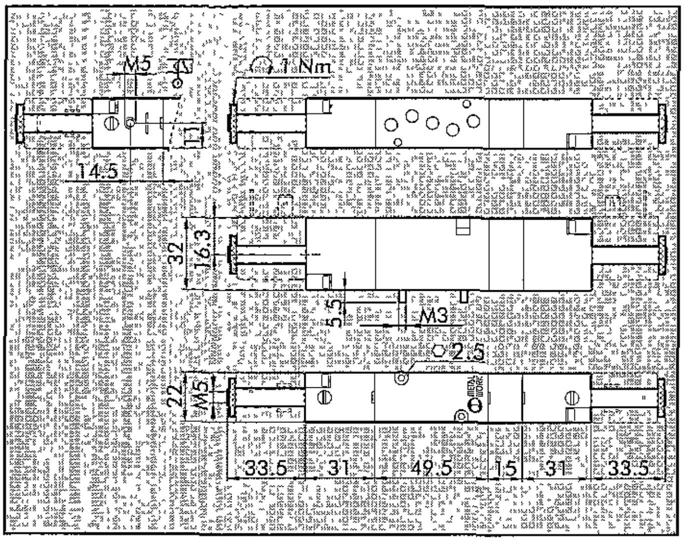
BISTABIL 5/2



Symbol	Benamning	Artikelnr	Vikt [g]
	SOV B5 SOB OO	7011021200	174
	SOV B5 SOD OO	7011021300	180
	SOV B5 SEB OO	7011021600	174



BISTABIL 5/3



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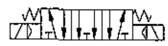
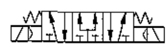
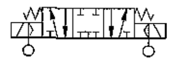
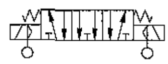
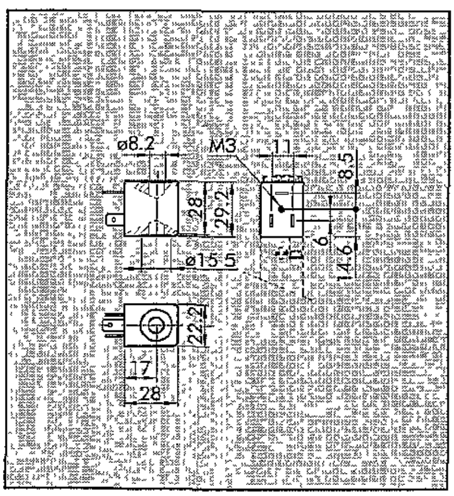
	SOV B6 SOS CC	7011022100	204
	SOV B6 SOS OC	7011022200	204
	SOV B6 SOS PC	7011022300	204
	SOV B6 SES CC	7011022400	202
	SOV B6 SES OC	7011022500	202
	SOV B6 SES PC	7011022600	202

2

TILLBEHÖR: SPOLAR OCH KONTAKTER

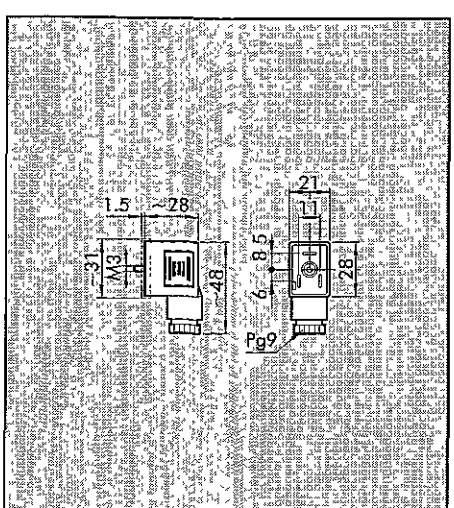
SPOLAR FÖR VENTILER SERIE 70, BASANSLUTNING



- Spänningstolerans: -10% + 15%
- Isoleringsklass F155
- Kapslingsklass IP65 EN60529 med kontakt
- Ej för kontinuerligt utomhusbruk
- Max. temperatur spole vid 100% ED: 70°C vid 20°C omgivningstemperatur

Nominell spanning	Effekt		Benämning	Artikelnr.
	Tillslag	Håll		
12Vcc	2W	2W	Spole 22 Ø8 BA 2W-12VDC	W0215000151
24Vcc	2W	2W	Spole 22 Ø8 BA 2W-24VDC	W0215000101
24V 50/60Hz	4VA	3VA	Spole 22 Ø8 BA 3VA-24VAC	W0215000111
110V 50/60Hz	4VA	3VA	Spole 22 Ø8 BA 3VA-110VAC	W0215000121
220V 50/60Hz	4VA	3VA	Spole 22 Ø8 BA 3VA-220VAC	W0215000131

KONTAKTER

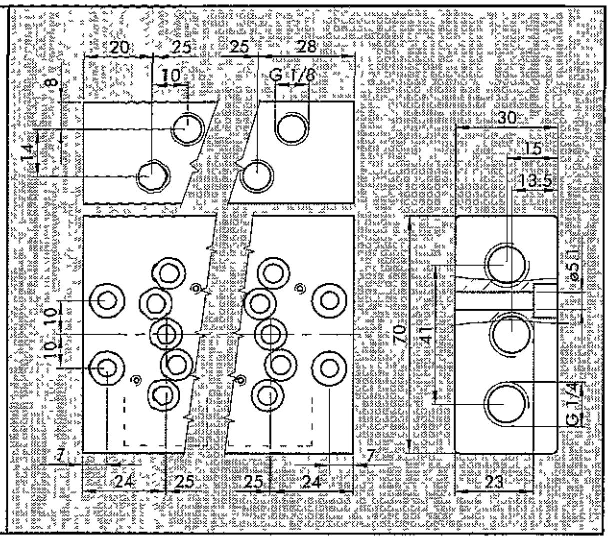


Färg	Ø Kabel	Benämning	Artikelnr.
Svart	PG9	Standard	W0970510011
Transparent	PG9	LED 24V	W0970510012
Transparent	PG9	LED 110V	W0970510013
Transparent	PG9	LED 220V	W0970510014
Transparent	PG9	LED + VDR 24V	W0970510015
Transparent	PG9	LED + VDR 110V	W0970510016
Transparent	PG9	LED + VDR 220V	W0970510017

TILLBEHÖR: MULTIPELBASPLATTOR FÖR VENTILER SERIE 70, BASANSLUTNING

MULTIPELBASPLATTA

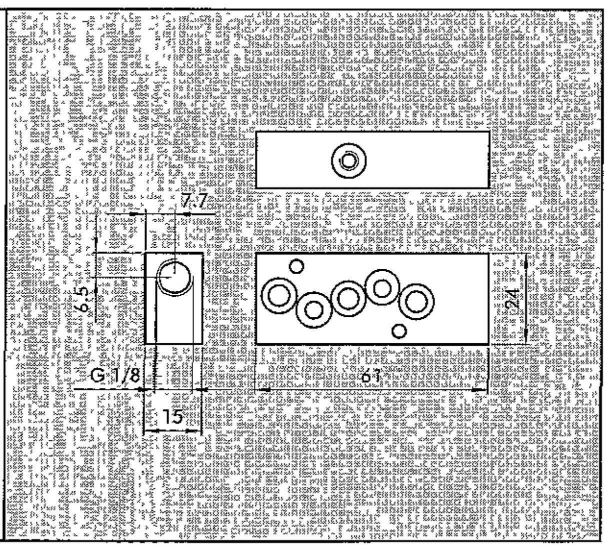
1



Artikelnr	Benämning	Vikt [g]
0223100201	Basplatta 2 positioner 1/8, basansl	341
0223100401	Basplatta 4 positioner 1/8, basansl.	591
0223100601	Basplatta 6 positioner 1/8, basansl	855
0223100801	Basplatta 8 positioner 1/8, basansl.	1093
0223101001	Basplatta 10 positioner 1/8, basansl	1352

MELLANPLATTA FÖR SEP. PÅLUFTNING

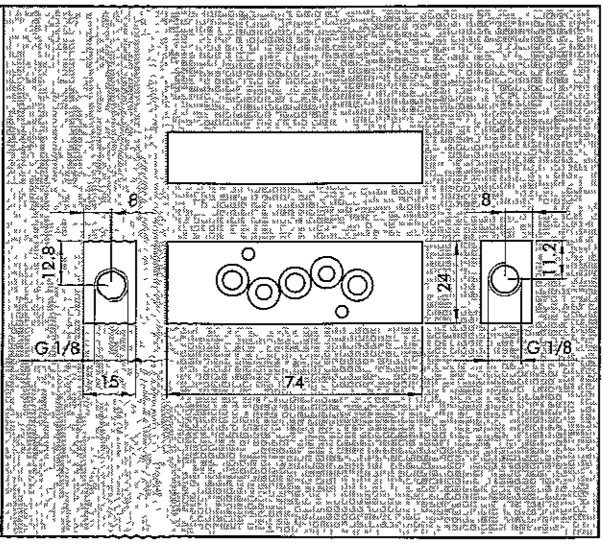
2



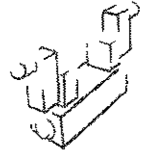
Artikelnr	Benämning	Vikt [g]
0223106301	Mellanplatta för sep. påluftning	65

MELLANPLATTA FÖR AVLUFTSTRYPNING

3

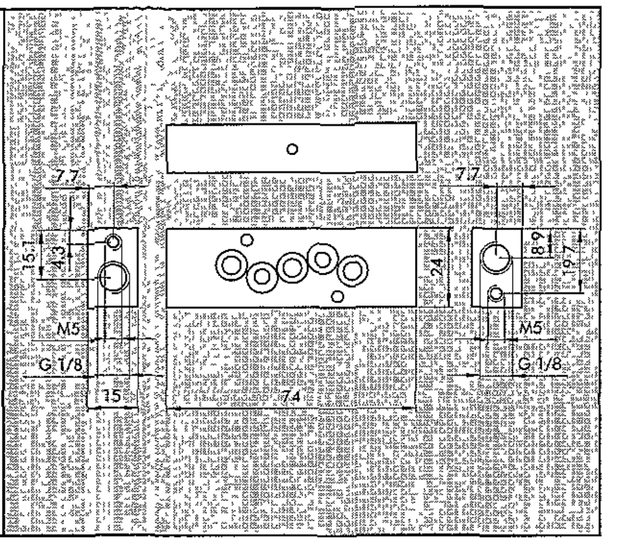


Artikelnr	Benämning	Vikt [g]
0223106303	Mellanplatta för avluftstrypning	75



MELLANPLATTA FÖR SEP. AVLUFTNING

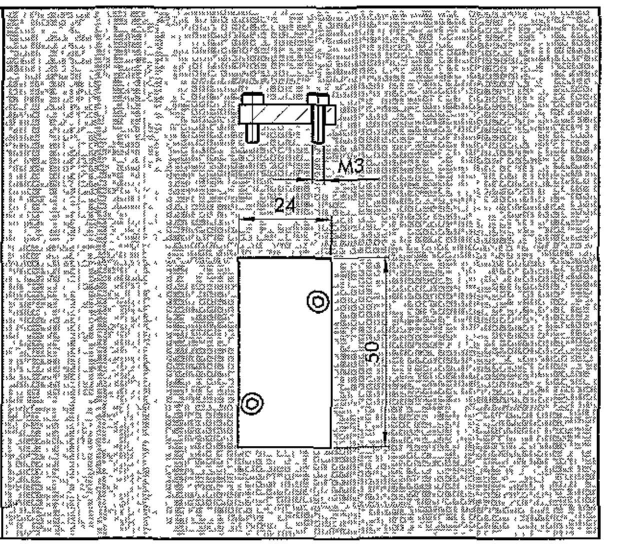
4



Artikelnr	Benämning	Vikt [g]
0223106302	Mellanplatta för sep. avluftning	75

BLINDPLATTA

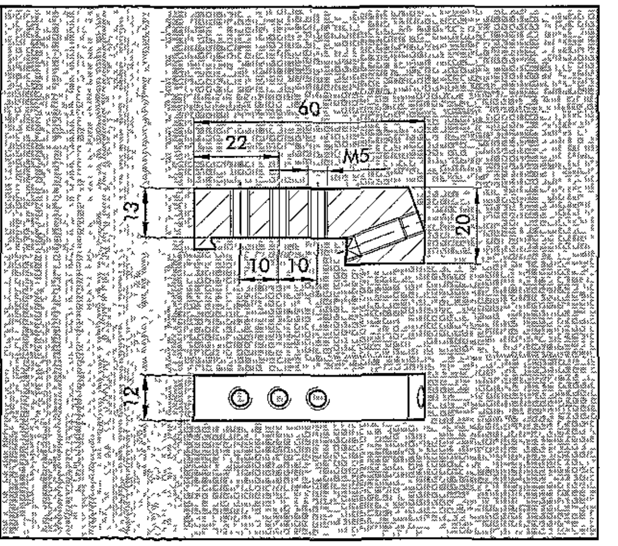
5



Artikelnr	Benämning	Vikt [g]
0223106500	Blindplatta 1/8, basanslutning	15

ADAPTER FÖR OMEGASKENA

6



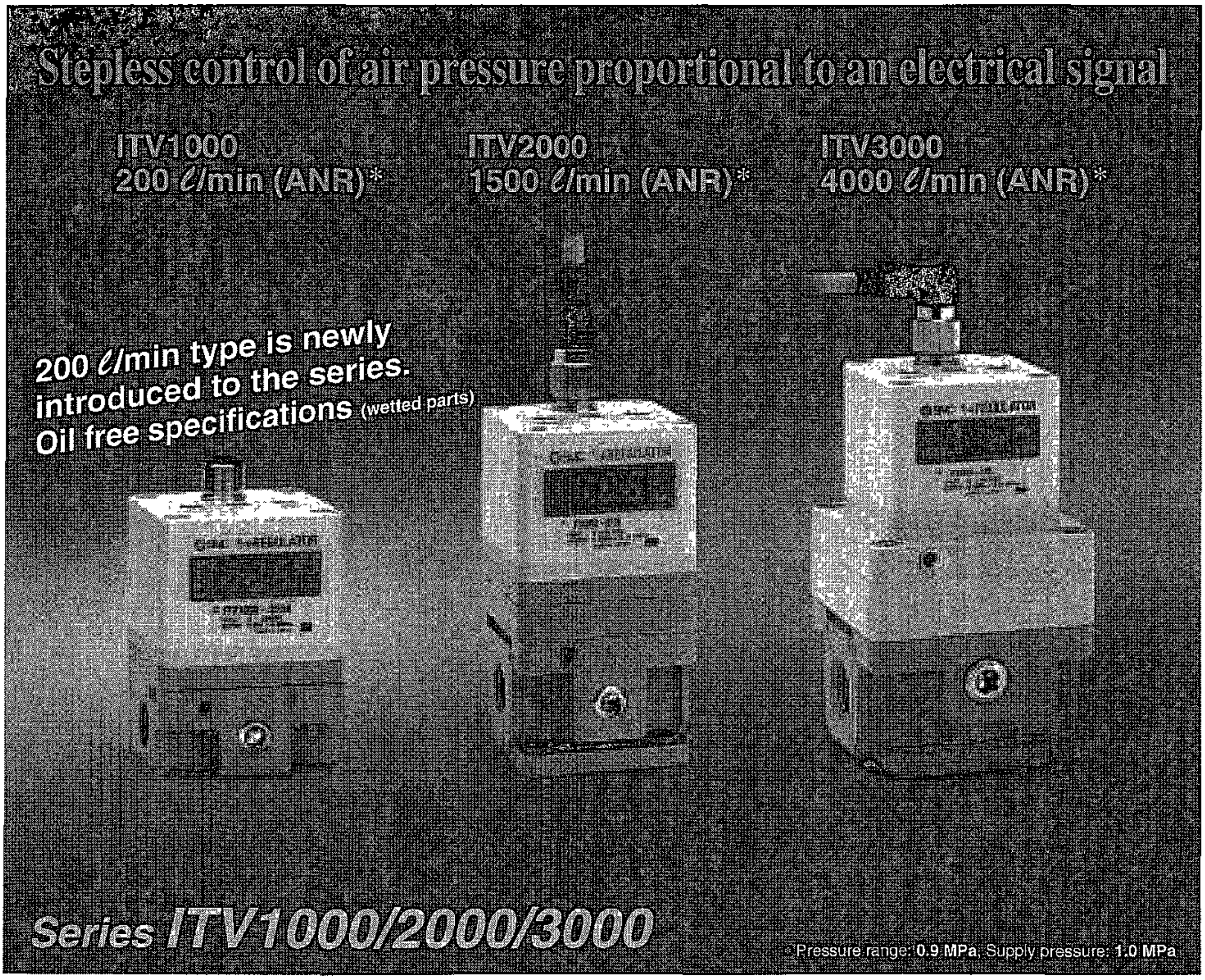
Artikelnr	Benämning	Vikt [g]
0226004600	Adapter för omegaskena	46

2

SMC®

CE
(Option)

Electro-Pneumatic Regulator



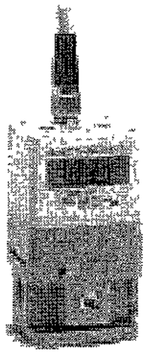
IP65

Sensitivity: 0.2 kPa (100 kPa specifications)

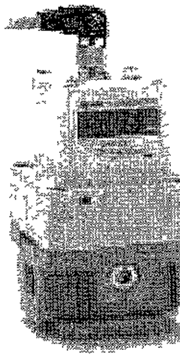
Linearity: Within ±1% (F.S.)

Hysteresis: Within ±0.5% (F.S.)

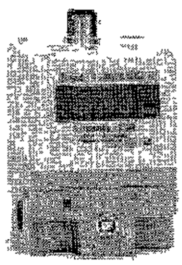
Electro-Pneumatic Regulator
Series ITV1000/2000/3000



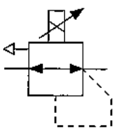
Straight type

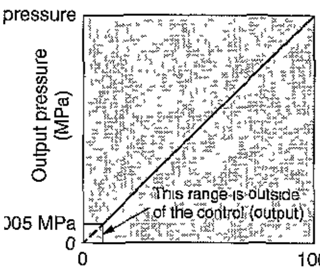


Right angle type



S Symbol





Input/output characteristics chart

Standard Specifications

Model		ITV101□ / ITV201□ / ITV301□	ITV103□ / ITV203□ / ITV303□	ITV105□ / ITV205□ / ITV305□
Minimum supply pressure		Set pressure +0.1 MPa		
Maximum supply pressure		0.2 MPa	1.0 MPa	
Set pressure range Note 1)		0.005 to 0.1 MPa	0.005 to 0.5 MPa	0.005 to 0.9 MPa
Power supply	Voltage	24 VDC ± 10%, 12 to 15 VDC		
	Current consumption	Power supply voltage 24 VDC type 0.12 A or less Power supply voltage 12 to 15 VDC type 0.18 A or less		
Input signal	Current type Note 2)	4 to 20 mA, 0 to 20 mA (Sink type)		
	Voltage type	0 to 5 VDC, 0 to 10 VDC		
	Preset input	4 points		
Input impedance	Current type	250 Ω or less		
	Voltage type	Approx. 6.5 kΩ		
	Preset input	Approx. 2.7 kΩ		
Output signal (monitor output) Note 3)	Analog output	1 to 5 VDC (Load impedance: 1 kΩ or more) 4 to 20 mA (Sink type) (Load impedance: 250 Ω or less)		
	Switch output	NPN open collector output: Max. 30 V, 30 mA PNP open collector output: Max. 30 mA		
Linearity		Within ±1% (full span)		
Hysteresis		Within 0.5% (full span)		
Repeatability		Within ±0.5% (full span)		
Sensitivity		Within 0.2% (full span)		
Temperature characteristics		Within ±0.12% (full span)/°C		
Output pressure display	Accuracy	±3% (full span)		
	Minimum unit	MPa: 0.01, kgf/cm²: 0.01, bar: 0.01, PSI: 0.1 Note 4), kPa: 1		
Ambient and fluid temperature		0 to 50°C (with no condensation)		
Enclosure		IP65		
Weight	ITV10□□	Approx. 250 g (without options)		
	ITV20□□	Approx. 350 g (without options)		
	ITV30□□	Approx. 645 g (without options)		

Note 1) Please refer to graph 1, relation to the differences between the set pressure and input.
Additionally, refer to the page 18 for the set pressure range by units of standard measured pressure.
Additionally, refer to page 18 as maximum set pressure differs on unit of standard measure.
Note 2) 2-wire type 4 to 20 mA is not available. Power supply voltage (24 VDC or 12 to 15 VDC) is required.
Note 3) Select either analog output or switch output.
Further, when switch output is selected, select either NPN output or PNP output.
Note 4) The minimum unit for ITV205□ is 1PSI.
Note 5) The above characteristics are confined to the static state. When air is consumed on the output side, the pressure may fluctuate.

How to Order

ITV 3 0 1 0 – 0 1 2 S – Q

Model

1	1000
2	2000
3	3000

Pressure range

1	0.1 MPa
3	0.5 MPa
5	0.9 MPa

Power supply voltage

0	24 VDC
1	12 to 15 VDC

Input signal

0	Current 4 to 20 mA (Sink type)
1	Current 0 to 20 mA (Sink type)
2	Voltage 0 to 5 VDC
3	Voltage 0 to 10 VDC
4*	Preset input

* Option

Monitor output

0*	None (for preset input)
1	Analog output 1 to 5V DC
2*	Switch output/NPN output
3*	Switch output/PNP output
4*	Analog output 4 to 20 mA (Sink type)

Option

Thread type

–	Rc
N*	NPT
T*	NPTF
F*	G

* Option

Port size

1	1/8 (1000 type)
2	1/4 (1000, 2000, 3000 type)
3	3/8 (2000, 3000 type)
4	1/2 (3000 type)

Cable connector type

S	Straight type 3 m
L*	Right angle type 3 m
N*	Without cable connector

* Option

Bracket

–	Without bracket
B*	Flat bracket
C*	L-bracket

* Option

Pressure display unit Note 1)

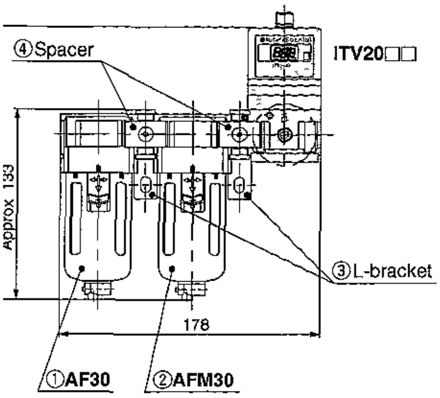
–	MPa
2*	kgf/cm²
3*	bar
4*	PSI
5*	kPa

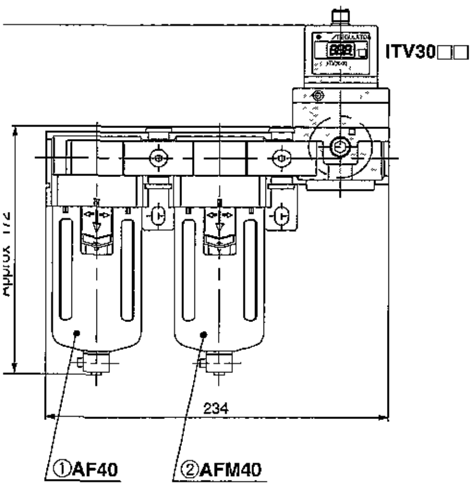
* Option

CE compliance

–	–
Q	CE compliant

* Please visit our SMC homepage http://www.smcworld.com for the latest details on our CE compliant products.





Combinations

◎ Standard specifications ○ Combination possible ▭ Combination not possible

∗ ITV10□□ models are not applicable

Specifications		Symbol	Applicable model	
			ITV20□□	ITV30□□
Standard specifications	Set pressure max. 0.1 MPa	1	◎	◎
	Set pressure max 0 5 MPa	3	◎	◎
	Set pressure max. 0.9 MPa	5	◎	◎
	Connection Rc 1/4	02	◎	◎
	Connection Rc 3/8	03	◎	◎
	Connection Rc 1/2	04		◎
Accessories	Bracket	B	○	○
	Bracket	C	○	○
Optional specifications	Connection NPT1/4	N02	○	○
	Connection NPT3/8	N03	○	○
	Connection NPT1/2	N04		○
	Connection G 1/4	F02	○	○
	Connection G 3/8	F03	○	○
	Connection G 1/2	F04		○

Modular Products and Accessory Combinations

∗ ITV10□□ models are not applicable

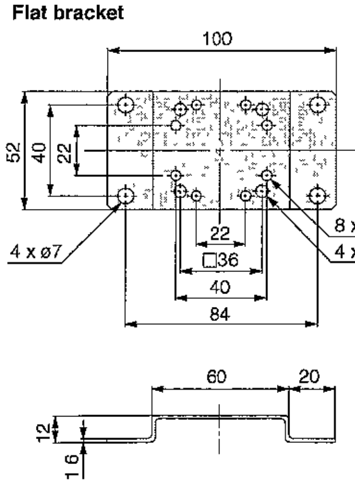
Applicable products and accessories	Applicable model	
	ITV20□□	ITV30□□
① Air filter	AF30	AF40
② Mist separator	AFM30	AFM40
③ L-bracket	B310L	B410L
④ Spacer	Y30	Y40
⑤ Spacer with L-bracket (③ + ④)	Y30L	Y40L

ccessories (Optional)/Part Numbers

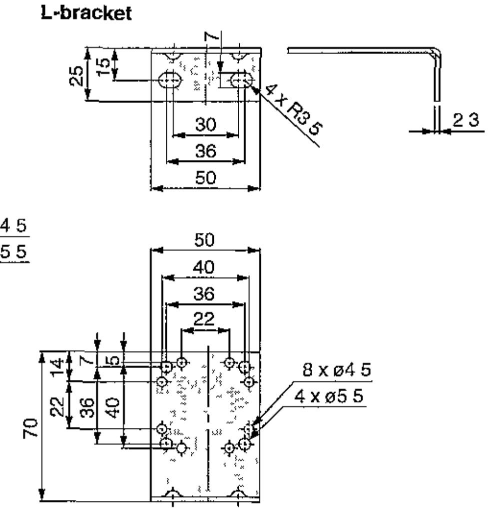
Description		Part No		
		ITV10□□	ITV20□□	ITV30□□
it bracket		P3020114 (Mounting thread is not included)		
bracket		INI-398-0-6 (Mounting thread is not included)		
connector	Straight type 3 m	TM-4DSX3HG4		
	Right angle type 3 m	TM-4DLX3HG4		

Dimensions

Flat bracket



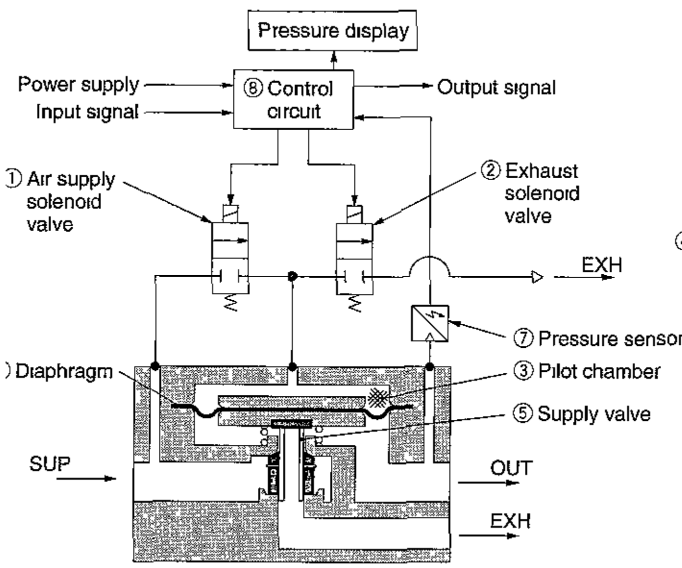
L-bracket



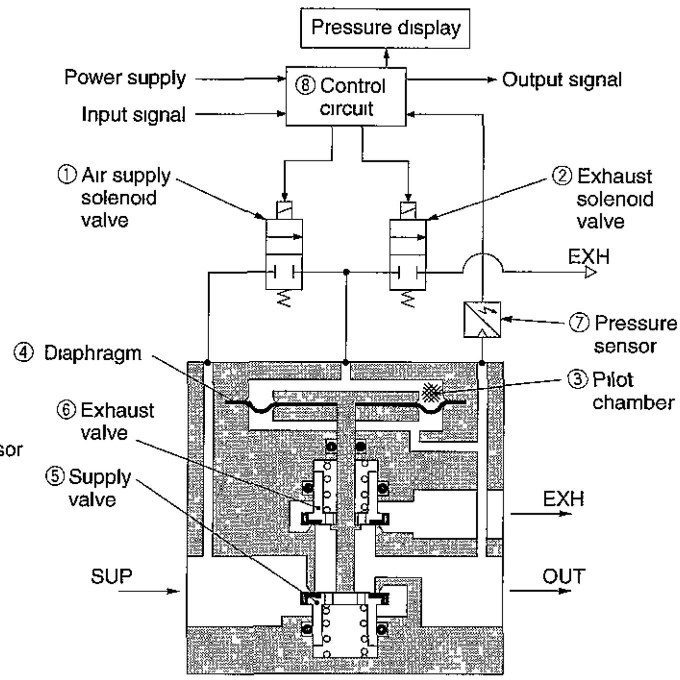
'orking Principles

ıen the ınput sıgnal rıses, the aır supply solenoıd valve ① turns ON, and the exhaust ;enoıd valve ② turns OFF Therefore, supply pressure passes through the aır supply 'enoıd valve ① and is applıed to the pılot chamber ③. The pressure ın the pılot ɜmber ③ ıncreases and operates on the upper surface of the dıaphragm ④.
a result, the aır supply valve ⑤ linked to the dıaphragm ④ opens, and a portıon of ; supply pressure becomes output pressure.
is output pressure feeds back to the control cırcuıt ⑧ vıa the pressure sensor ⑦. re, a correct operation functıons until the output pressure ıs proportıonal to the ınput nal, makıng ıt possıble to always obtaın output pressure proportıonal to the ınput ınal.

Working Principle Diagram

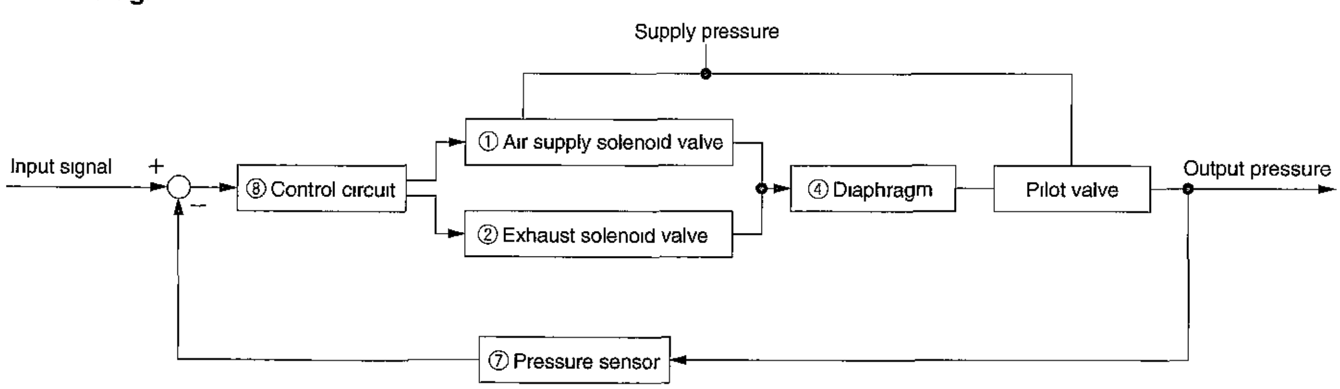


ITV1000



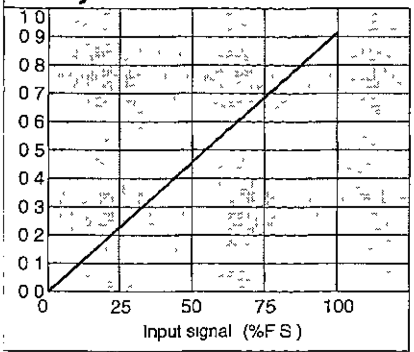
ITV2000, 3000

Block diagram

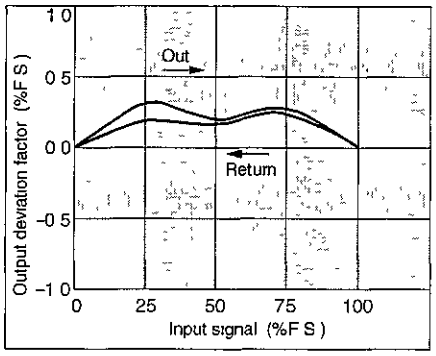


eries ITV105□

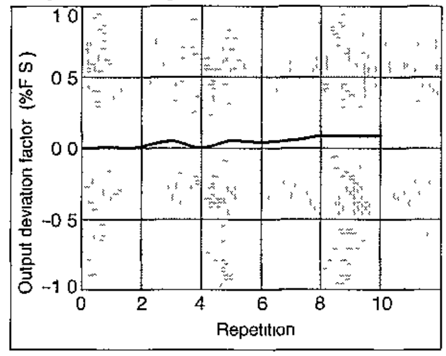
nearity



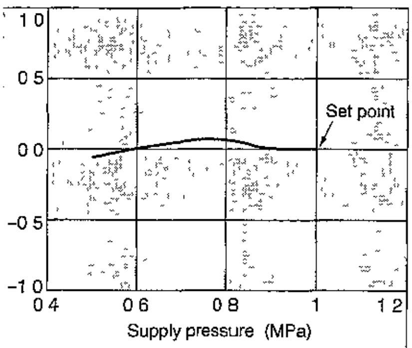
Hysteresis



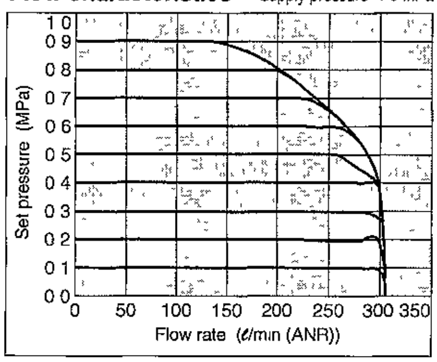
Repeatability



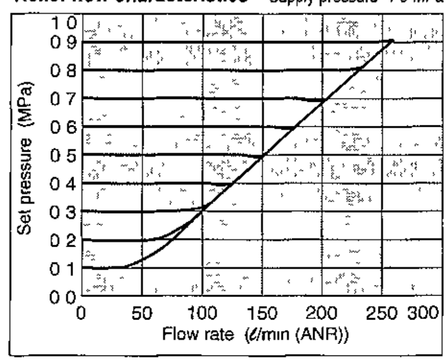
essure characteristics Set pressure 0 4 MPa



Flow characteristics Supply pressure 1 0 MPa

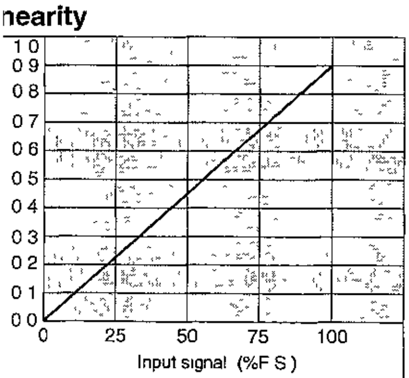


Relief flow characteristics Supply pressure 1 0 MPa

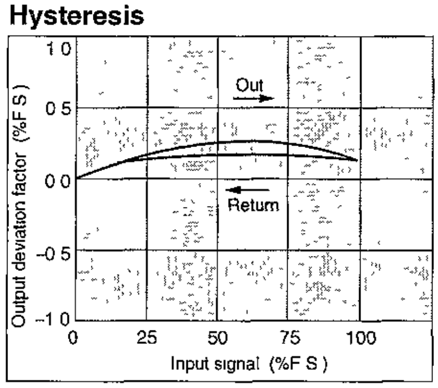


eries ITV205□

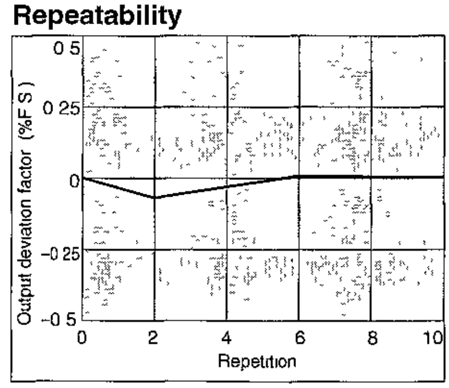
nearity



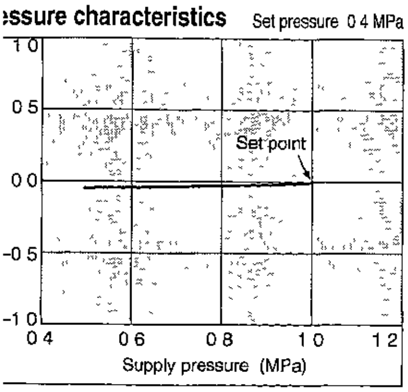
Hysteresis



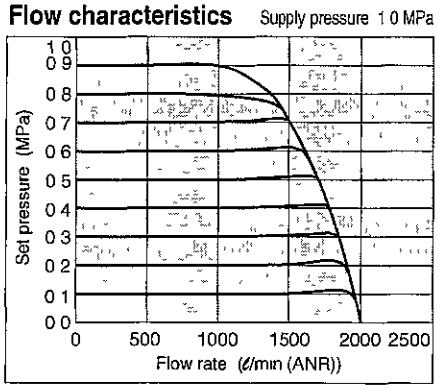
Repeatability



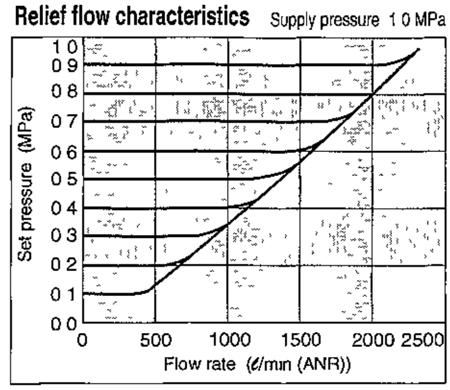
essure characteristics Set pressure 0 4 MPa



Flow characteristics Supply pressure 1 0 MPa



Relief flow characteristics Supply pressure 1 0 MPa

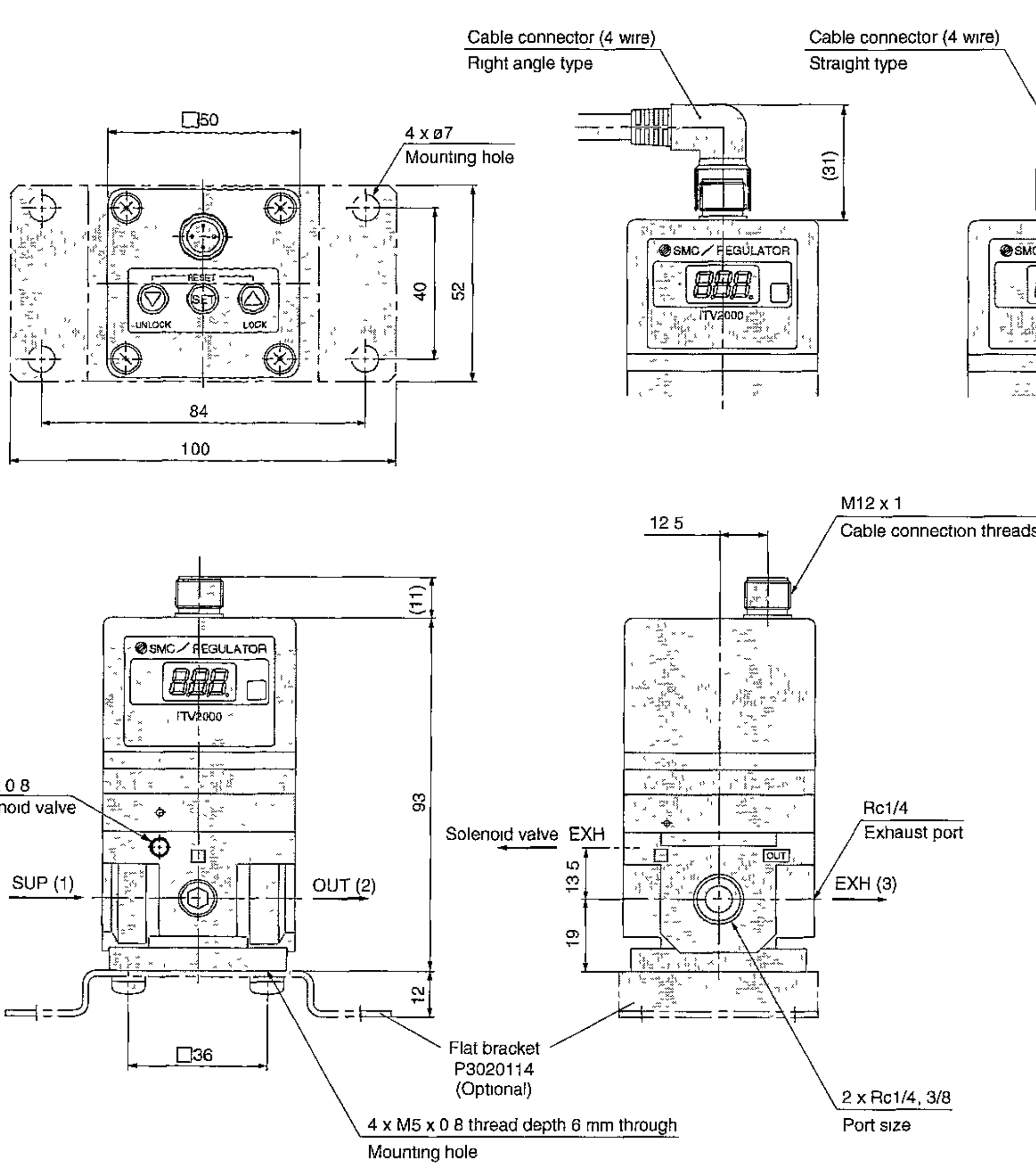


imensions

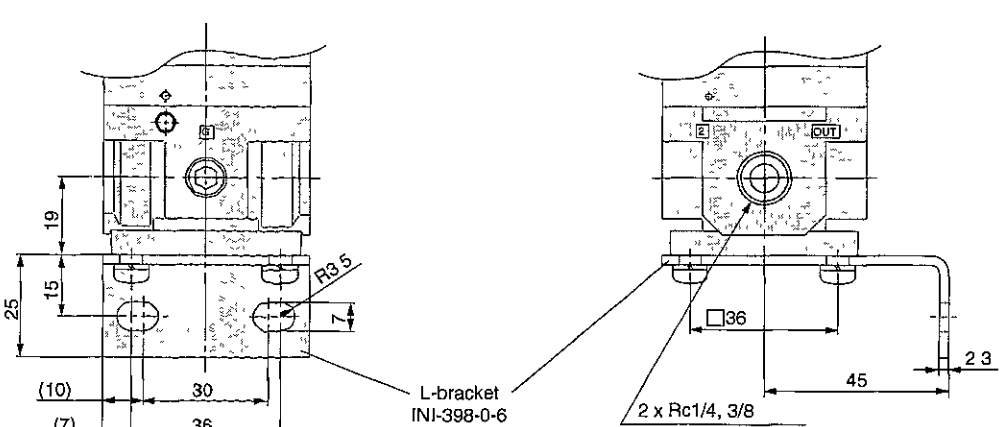
V20□□

at bracket

Note) Do not attempt to rotate, as the cable connector does not turn



bracket



Manifold Specifications (Except Series ITV3000)

hrough 8 station manifold.

ow to Order Manifolds

IITV20 — ☐ 02 — 5

ITV1000, 2000

Connection thread type

—	PT
N	NPT
F	PF

OUT port size

02	1/4
03	3/8

Valve stations

2	2 stations
:	:
8	8 stations

How to Order Manifold Assemblies

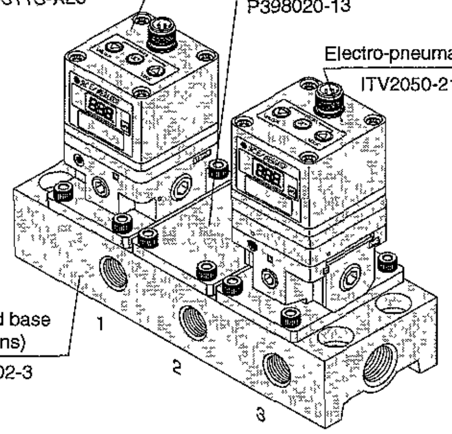
Example

Electro-pneumatic regulator
ITV1030-311S-X26

Blanking plate assembly
P398020-13

Electro-pneumatic regulator
ITV2050-212S-X26

Manifold base
(3 stations)
IITV20-02-3



TV20-02-3	1 set (3 station manifold base part no)
ITV2030-311S-X26	1 set (Electro-pneumatic regulator part no) Note 2)
P398020-13	1 set (Blanking plate assembly part no)
ITV2050-212S-X26	1 set (Electro-pneumatic regulator part no) Note 2)

→ The * is the symbol for mounting Add the * symbol at the beginning of part numbers for electro-pneumatic regulators, etc to be mounted on the base

te) Refer to the table below for possible mixed combination

Model	ITV101☐	ITV103☐	ITV105☐	ITV201☐	ITV203☐	ITV205☐
V101☐	●	—	—	●	—	—
V103☐	—	●	●	—	●	●
V105☐	—	●	●	—	●	●
V201☐	●	—	—	●	—	—
V203☐	—	●	●	—	●	●
V205☐	—	●	●	—	●	●

Note 1) Electro-pneumatic regulators are counted starting from station 1 on the left side with the OUT ports in front
Note 2) The port size for mounted electro-pneumatic regulators is Rc1/8 (ITV1000), Rc1/4 (ITV2000) only
Note 3) When there is a large number of stations, use piping with the largest possible inside diameter for the supply side, such as steel piping
Note 4) The use of the straight type cable connector is recommended
To mount right angle type, be certain to check that no possible interference occurs
Note 5) When mounting a blanking plate and the regulator with different pressure set, please inform SMC of the order of a manifold station beside a purchase order

High-Speed Response Time Specifications

essure response with no load is approx 0 1 sec

ITV 2 0 1 0 — 0 1 ☐ 2 ☐ S ☐ —X88

Model

1	1000 type
2	2000 type

Pressure range

1	0 1 MPa
3	0 5 MPa
5	0 9 MPa

Power supply voltage

0	24 VDC
1	12 to 15 VDC

Input signal

0	Current 4 to 20 mA (Sink type)
1	Current 0 to 20 mA (Sink type)
2	Voltage 0 to 5 VDC
3	Voltage 0 to 10 VDC

Monitor output

	Analog output 1 to 5V DC
	Switch output/NPN output
	Switch output/PNP output
	Analog output 4 to 20 mA (Sink type)

Thread type

—	Rc
N	NPT
T	NPTF
F	G

Port size

1	1/8 (1000 type)
2	1/4 (1000, 2000 type)
3	3/8 (2000 type)

Bracket

—	Without bracket
B	Flat bracket
C	L-bracket

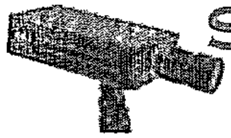
Cable connector type

S	Straight type 3 m
L	Right angle type 3 m
N	Without cable connector

Pressure display unit

—	MPa
2	kgf/cm²
3	bar
4	PSI
5	kPa

High-speed response time specifications



SPECIFICATIONS

CITIUS IMAGING HIGH SPEED VIDEO CAMERA C10

The high speed camera works in close co-operation with a PC (desktop or briefcase model), which is used for controlling, display and storage. The camera itself is a single unit and it is connected to the PC through the USB bus. Several cameras can be connected to the PC and operated simultaneously.

Resolution 652 x 496 pixels maximum, 40 x 20 pixels minimum, adjustable.

Recording speed Speed and maximum recording time depend on resolution used.
The following values are examples of combinations that can be attained.

Resolution (pixels)	Speed (frames/s)	Max.recording time (s)	
		256 MB memory	2 GB memory
640 x 480	99	8.9	70.9
340 x 256	330	9.3	74.7
172 x 128	1154	10.6	84.5
84 x 64	3551	14.1	112.5
40 x 20	10652	31.5	252

Sensitivity Two levels, corresponding to 800-1600 ISO

Exposure time Adjustable. Minimum exposure time is related to frame width:
10 - 43 μs (width 40 - 652 pixels)

Gray scale 256 level

Antiblooming 1/1000

Storage technique The video is first stored to the RAM-memory in the camera. From there it is transferred onto the PC hard disk. The camera can be furnished with the amount of memory from 256 MB to 2 GB.

Power supply Separate AC adapter (15 VDC/2.5 A) or 12 V battery.

Triggering Isolated 5..24 V or contact closure (polarity selectable)

Stroboscope control TTL-level, not isolated.

Indicators 4 LED´s.

Cable Between PC and camera: 5 m. With chained USB hubs max. 25 m.

Optics 1/3" or 1/2" C (CS)-mount lenses.
Electronically controlled (focus, zoom and iris) lences are available.

Tripod 1/4" thread

Dimensions 250 x 141 x 70 mm (excl. optics), Weight 1 kg

Sofware Runs on Windows 98, 98 SE, Me, 2000, XP

CENTRAL EUROPEAN CUSTOMERS:

L.O.T.-Oriel GmbH
Im Tiefen See 58
D-64293 Darmstadt Germany
www.lot-oriel.de

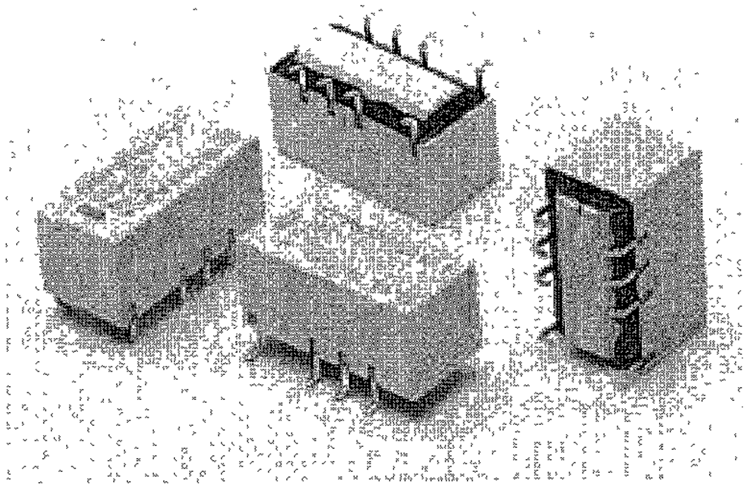
CITIUS IMAGING

CITIUS IMAGING LTD
TYYNELANKATU 6
24260 SALO, FINLAND
INFO@CITIUSIMAGING.COM
WWW.CITIUSIMAGING.COM

PCB Relay — G6S

Surface Mount DPDT Relay

- Long terminals for ideal for soldering and mounting reliability.
- Space-saving inside-L terminal
- High dielectric strength between coil and contacts (2,000 VAC), and between contacts of different polarity (1,500 VAC).
- High impulse withstand voltages between coil and contacts, and between contacts of different polarity (2,500 V, 2 x 10 µs Bellcore requirements)
- Low power consumption (140 mW).
- Bifurcated crossbar contact (Au-clad) and plastic sealed construction for high reliability.
- Applicable to IRS.
- High sealability after IRS.
- Ultra-miniature at 15 x 7.5 x 9.4 mm (L x W x H)
- Through-hole terminal is available
- EN60950/EN41003 Supplementary Insulation-certified type is available



Ordering Information

Classification				Single-side stable	Single-winding latching	Double-winding latching	Single-side stable EN60950/EN41003
DPDT	Plastic sealed	Through-hole terminal		G6S-2	G6SU-2	G6SK-2	G6S-2-Y
		Surface mount terminal	Inside-L	G6S-2G	G6SU-2G	G6SK-2G	G6S-2G-Y
			Outside-L	G6S-2F	G6SU-2F	G6SK-2F	G6S-2F-Y

Note: 1 When ordering, add the rated coil voltage to the model number
Example. G6S-2F 12 VDC
Rated coil voltage

2 When ordering tape packing, add "-TR" to the model number
Example. G6S-2F-TR 12 VDC
Tape packing

Be sure since "-TR" is not part of the relay model number, it is not marked on the relay case

Model Number Legend:

G6S□-□□-□ □VDC

1 2 3 4 5

1. **Relay Function**
   None Single-side stable
   U Single-winding latching
   K: Double-winding latching
2. **Contact Form**
   2: DPDT
3. **Terminal Shape**
   None Through-hole terminal
   G. Inside-L surface mount terminal
   F: Outside-L surface mount terminal
4. **Approved Standards**
   None: UL/CSA
   Y EN60950/EN41003
5. **Rated Coil Voltage**
   (Refer to "Coil Ratings")

Specifications

Coil Ratings

Single-side Stable Type (G6S-2, G6S-2F, G6S-2G)

Rated voltage	4 5 VDC	5 VDC	12 VDC	24 VDC
Rated current	31 0 mA	28 1 mA	11 7 mA	8 3 mA
Coil resistance	145 Ω	178 Ω	1,028 Ω	2,880 Ω
Must operate voltage	75% max of rated voltage			
Must release voltage	10% min of rated voltage			
Max. voltage	200% of rated voltage at 23°C, 130% at 85°C			170% of rated voltage at 23°C, 130% at 85°C
Power consumption	Approx 140 mW			Approx 200 mW

Note: 1. The rated current and coil resistance are measured at a coil temperature of 23°C with a tolerance of ±10%

2 Operating characteristics are measured at a coil temperature of 23°C

Single-winding Latching Type (G6SU-2, G6SU-2F, G6SU-2G)

Rated voltage		4 5 VDC	5 VDC	12 VDC	24 VDC
Rated current		22 2 mA	20 mA	8 3 mA	6 3 mA
Coil resistance		203 Ω	250 Ω	1,440 Ω	3,840 Ω
Coil inductance (H) (ref. value)	**Armature OFF**	0 27	0 36	2 12	5 80
	Armature ON	0.14	0 18	1 14	3 79
Must set voltage		75% max of rated voltage			
Must reset voltage		75% max. of rated voltage			
Max. voltage		180% of rated voltage at 23°C, 140% at 85°C			
Power consumption		Approx 100 mW			Approx 150 mW

Note: 1 The rated current and coil resistance are measured at a coil temperature of 23°C with a tolerance of ±10%.

2 Operating characteristics are measured at a coil temperature of 23°C

Double-winding Latching Type (G6SK-2, G6SK-2F, G6SK-2G)

Rated voltage			4 5 VDC	5 VDC	12 VDC	24 VDC
Rated current			44 4 mA	40 mA	16 7 mA	12 5 mA
Coil resistance			101 Ω	125 Ω	720 Ω	1,920 Ω
Coil inductance (H) (ref. value)	**Set**	**Armature OFF**	0 12	0 14	0 60	1.98
		Armature ON	0 074	0.088	0.41	1 23
	Reset	**Armature OFF**	0 082	0 098	0.46	1 34
		Armature ON	0 14	0.16	0 54	2 23
Must set voltage			75% max of rated voltage			
Must reset voltage			75% max. of rated voltage			
Max. voltage			170% of rated voltage at 23°C, 130% at 85°C			140% of rated voltage at 23°C, 110% at 70°C
Power consumption			Approx 200 mW			Approx 300 mW

Note: 1. The rated current and coil resistance are measured at a coil temperature of 23°C with a tolerance of ±10%

2 Operating characteristics are measured at a coil temperature of 23°C

Single-side Stable EN60950/EN41003 Approved Type (G6S-2-Y, G6S-2F-Y, G6S-2G-Y)

Rated voltage	5 VDC	12 VDC	24 VDC
Rated current	40 mA	16 7 mA	9 6 mA
Coil resistance	125 Ω	720 Ω	2,504 Ω
Must operate voltage	75% max of rated voltage		
Must release voltage	10% min of rated voltage		
Max. voltage	170% of rated voltage at 23°C, 130% at 85°C		170% of rated voltage at 23°C, 110% at 70°C
Power consumption	Approx 200 mW		Approx 230 mW

Note: 1 The rated current and coil resistance are measured at a coil temperature of 23°C with a tolerance of ±10%.

2. Operating characteristics are measured at a coil temperature of 23°C

Contact Ratings

Load	Resistive load (cosϕ = 1)
Rated load	0 5 A at 125 VAC, 2 A at 30 VDC
Contact material	Ag (Au-clad)
Rated carry current	2 A
Max. switching voltage	250 VAC, 220 VDC
Max. switching current	2 A
Max. switching capacity	62 5 VA, 60 W
Min. permissible load	10 µA at 10 mVDC

Note: P level λ_{60} = 0 1 x 10^{-6}/operation

Characteristics

Contact resistance	75 mΩ max
Operate (set)time	4 ms max (mean value. approx 2 5 ms, latching type approx 2 ms)
Release (reset) time	4 ms max (mean value approx 1 5 ms, latching type approx 2 ms)
Bounce time	Operate Approx 0 5 ms Release· Approx 0 5 ms Set/Reset Approx 0 5 ms
Max. operating frequency	Mechanical 36,000 operations/hr Electrical 1,800 operations/hr (under rated load)
Insulation resistance	1,000 MΩ min (at 500 VDC)
Dielectric strength	2,000 VAC, 50/60 Hz for 1 min between coil and contacts 1,000 VAC, 50/60 Hz for 1 min between coil and contacts (double-winding latching) 1,500 VAC, 50/60 Hz for 1 min between contacts of different polarity 1,000 VAC, 50/60 Hz for 1 min between contacts of same polarity 500 VAC, 50/60 Hz for 1 min between set and reset coil (double-winding latching)
Impulse withstand voltage	2,500 V, 2 x 10 µs between coil and contacts 1,500 V, 10 x 160 µs between coil and contacts (double-winding latching) 2,500 V, 2 x 10 µs between contacts of different polarity 1,500 V, 10 x 160 µs between contacts of same polarity (conforms to FCC Part 68)
Vibration resistance	Destruction. 10 to 55 Hz, 5-mm double amplitude Malfunction 10 to 55 Hz, 3 3-mm double amplitude
Shock resistance	Destruction. 1,000 m/s² (approx 100G) Malfunction 750 m/s² (approx. 75G)
Life expectance	Mechanical 100,000,000 operations min (at 36,000 operations/hr) Electrical 100,000 operations min (2 A at 30 VDC, resistive load 1,200 operations/hr) 100,000 operations min (0.5 A at 125 VAC, resistive load)
Ambient temperature	Operating –40°C to 85°C (with no icing), –40°C to 70°C (double-winding latching, 24 VDC) Storage –40°C to 85°C (with no icing)
Ambient humidity	Operating. 35% to 85%
Weight	Approx 2 g

Approved Standards

UL1950 (File No. E41515)/CSA C22.2 No.950 (File No. LR24825)

Model	Contact form	Coil ratings	Contact ratings
G6S-2, G6S-2F, G6S-2G	DPDT	1 5 to 48 VDC	2 A, 30 VDC 0 3 A, 110 VDC 0.5 A, 125 VAC
G6SU-2, G6SK-2, G6SU-2F, G6SU-2G, G6SK-2F, G6SK-2G		1 5 to 24 VDC	

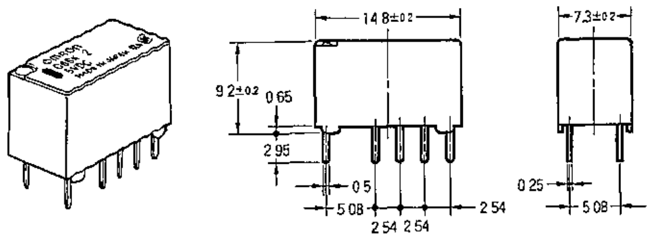
EN60950/EN41003

Model	Contact form	Isolation category	Voltage
G6S-2-Y, G6S-2G-Y, G6S-2F-Y	DPDT	Supplementary Isolation	250 VAC

Double-winding Latching

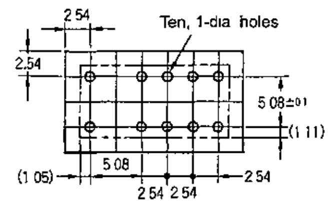
G6SK-2

Tolerance: ±0 3

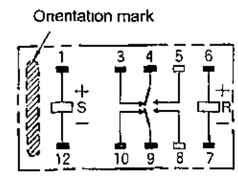


Footprint (Bottom View)

Tolerance ±0 1

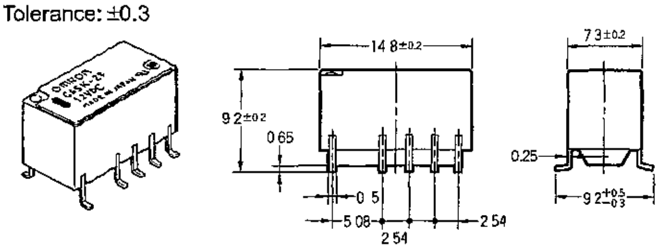


Terminal Arrangement/ Internal Connections (Bottom View)



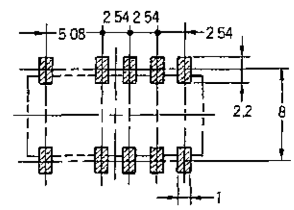
G6SK-2F

Tolerance: ±0.3

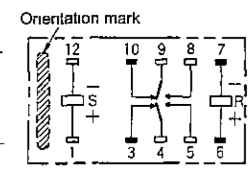


Footprint (Top View)

Tolerance ±0 1

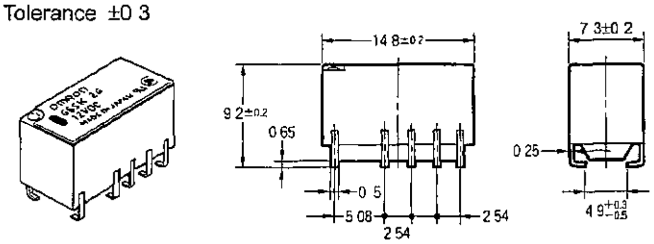


Terminal Arrangement/ Internal Connections (Top View)



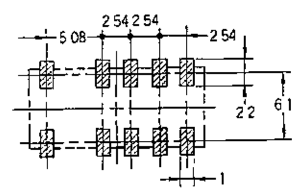
G6SK-2G

Tolerance ±0 3

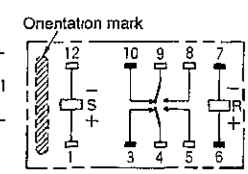


Footprint (Top View)

Tolerance ±0 1



Terminal Arrangement/ Internal Connections (Top View)



Low-Cost E Series Multifunction DAQ
12 or 16-Bit, 200 kS/s, 16 Analog Inputs

E Series – Low-Cost

- 16 analog inputs at up to 200 kS/s, 12 or 16-bit resolution
- Up to 2 analog outputs at 10 kS/s, 12 or 16-bit resolution
- 8 digital I/O lines (TTL/CMOS); two 24-bit counter/timers
- Digital triggering
- 4 analog input signal ranges
- NI-DAQ driver simplifies configuration and measurements

Families
- NI 6036E
- NI 6034E
- NI 6025E
- NI 6024E
- NI 6023E

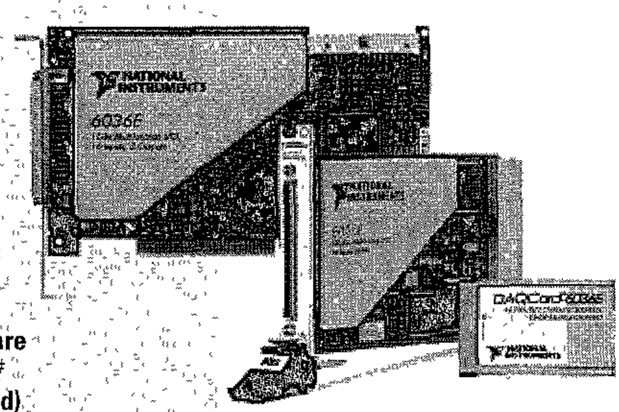
Operating Systems
- Windows 2000/NT/XP
- Real-time performance with LabVIEW
- Others such as Linux and Mac OS X

Recommended Software
- LabVIEW
- LabWindows/CVI
- Measurement Studio
- VI Logger

Other Compatible Software
- Visual Basic, C/C++, and C#

Driver Software (included)
- NI-DAQ 7

Calibration Certificate Included



Family	Bus	Analog Inputs	Input Resolution	Max Sampling Rate	Input Range	Analog Outputs	Output Resolution	Output Rate	Output Range	Digital I/O	Counter/Timers	Triggers
NI 6036E	PCI, PCMCIA	16 SE/8 DI	16 bits	200 kS/s	±0 05 to ±10 V	2	16 bits	10 kS/s[1]	±10 V	8	2, 24-bit	Digital
NI 6034E	PCI	16 SE/8 DI	16 bits	200 kS/s	±0 05 to ±10 V	0	-	-	-	8	2 24 bit	Digital
NI 6025E	PCI, PXI	16 SE/8 DI	12 bits	200 kS/s	±0 05 to ±10 V	2	12 bits	10 kS/s[1]	±10 V	8	2, 24-bit	Digital
NI 6024E	PCI, PCMCIA	16 SE/8 DI	12 bits	200 kS/s	±0 05 to ±10 V	2	12 bits	10 kS/s[1]	±10 V	8	2, 24-bit	Digital
NI 6023E	PCI	16 SE/8 DI	12 bits	200 kS/s	±0 05 to ±10 V	0	-	-	-	8	2, 24-bit	Digital

[1] 10 kS/s typical when using the single DMA channel for analog out put. 1kS/s maximum when using the single DMA channel for either analog input or counter/timer operations 1 kS/s maximum for PCMCIA DAQCards in all cases

Table 1 NI Low-Cost E Series Model Guide

Overview and Applications

NI low-cost E Series multifunction data acquisition devices provide full functionality at a price to meet the needs of the budget-conscious user They are ideal for applications ranging from continuous high-speed data logging to control applications to high-voltage signal or sensor measurements when used with NI signal conditioning Synchronize the operations of multiple devices using the RTSI bus or PXI trigger bus to easily integrate other hardware such as motion control and machine vision to create an entire measurement and control system.

Highly Accurate Hardware Design

NI Low-Cost E Series DAQ devices include the following features and technologies

Temperature Drift Protection Circuitry – Designed with components that minimize the effect of temperature changes on measurements to less than 0.0010% of reading per °C

Resolution-Improvement Technologies – Carefully designed noise floor maximizes the resolution

Onboard Self-Calibration – Precise voltage reference included for calibration and measurement accuracy Self-calibration is completely software controlled, with no potentiometers to adjust.

NI DAQ-STC – Timing and control ASIC designed to provide more flexibility, lower power consumption, and a higher immunity to noise and jitter than off-the-shelf counter/timer chips

NI MITE – ASIC designed to optimize data transfer for multiple simultaneous operations using bus mastering with one DMA channel, interrupts, or programmed I/O.

NI PGIA – Measurement and instrument class amplifier that guarantees settling times at all gains Typical commercial off-the-shelf amplifier components do not meet the settling time requirements for high-gain measurement applications.

PFI Lines – Eight programmable function input (PFI) lines that can be used for software-controlled routing of interboard and intraboard digital and timing signals

NATIONAL INSTRUMENTS™

Low-Cost E Series Multifunction DAQ
12 or 16-Bit, 200 kS/s, 16 Analog Inputs

		Full-Featured E Series				Low-Cost E Series		Basic
Models		NI 6030E, NI 6031E, NI 6032E, NI 6033E	NI 6052E	NI 6070E, NI 6071E	NI 6040E	NI 6034E, NI 6036E	NI 6023E, NI 6024E, NI 6025E	PCI-6013, PCI-6014
Measurement Sensitivity* (mV)		0.0023	0.0025	0.009	0.008	0.0036	0.008	0.004
Nominal Range (V)		Absolute Accuracy (mV)						
Positive FS	Negative FS							
10	10	1.147	4.747	14.369	15.373	7.560	16.504	8.984
5	-5	2.077	0.876	5.193	5.697	1.790	5.263	2.003
2.5	-2.5	–	1.190	3.605	3.859	–	–	–
2	-2	0.836	–	–	–	–	–	–
1	-1	0.422	0.479	1.452	1.556	–	–	–
0.5	-0.5	0.215	0.243	0.735	0.789	0.399	0.846	0.471
0.25	-0.25	–	0.137	0.379	0.405	–	–	–
0.2	-0.2	0.102	–	–	–	–	–	–
0.1	-0.1	0.061	0.064	0.163	0.176	–	–	–
0.05	-0.05	–	0.035	0.091	0.100	0.0611	0.106	0.069
10	0	0.976	1.232	6.765	7.269	–	–	–
5	0	1.992	2.119	5.391	5.645	–	–	–
2	0	0.802	0.850	2.167	2.271	–	–	–
1	0	0.405	0.428	1.092	1.146	–	–	–
0.5	0	0.207	0.242	0.558	0.583	–	–	–
0.2	0	0.098	0.111	0.235	0.247	–	–	–
0.1	0	0.059	0.059	0.127	0.135	–	–	–

Note Accuracies are valid for measurements following an internal calibration. Measurement accuracies are listed for operational temperatures within ±1 °C of internal calibration temperature and ±10 °C of external or factory-calibration temperature. One year calibration interval recommended. The Absolute Accuracy at Full Scale calculations were performed for a maximum range input voltage (for example 10 V for the ±10 V range) after one year assuming 100 pt averaging of data. *Smallest detectable voltage change in the input signal at the smallest input range

Table 2 Low-Cost E Series Analog Input Absolute Accuracy Specifications

		Full-Featured E Series				Low-Cost E Series		Basic
Models		NI 6030E, NI 6031E, NI 6032E, NI 6033E	NI 6052E	NI 6070E, NI 6071E	NI 6040E	PCI 6036E	PCI-6024E, NI 6025E	NI 6013, NI 6014
Nominal Range (V)		Absolute Accuracy (mV)						
Positive FS	Negative FS							
10	-10	1.43	1.405	8.127	8.127	2.417	8.127	3.835
10	0	1.201	1.176	5.685	5.685	–	–	–

Table 3 Low-Cost E Series Analog Output Absolute Accuracy Specifications

RTSI or PXI Trigger Bus – Used to share timing and control signals between multiple devices to synchronize operations.

RSE Mode – In addition to differential and nonreferenced single-ended modes, NI low-cost E Series devices offer referenced single-ended (RSE) mode for use with floating signal sources in applications with channel counts higher than eight

Onboard Temperature Sensor – Included for monitoring the operating temperature of the device to ensure that it is operating within the specified range

High-Performance, Easy-to-Use Driver Software

NI-DAQ is the robust driver software that makes it easy to access the functionality of your data acquisition hardware, whether you are a beginning or advanced user. Helpful features include

Automatic Code Generation – The DAQ Assistant is an interactive guide that steps you through configuring, testing, and programming measurement tasks and generates the necessary code automatically for LabVIEW, LabWindows/CVI, or Measurement Studio.

Cleaner Code Development – Basic and advanced software functions have been combined into one easy-to-use yet powerful set to help you build cleaner code and move from basic to advanced applications without replacing functions.

High-Performance Driver Engine – Software-timed single-point input (typically used in control loops) with NI-DAQ achieves rates of up to 50 kHz. NI-DAQ also delivers maximum I/O system throughput with a multithreaded driver.

Test Panels – With NI-DAQ, you can test all of your device functionality before you begin development.

Scaled Channels – Easily scale your voltage data into the proper engineering units using the NI-DAQ Measurement Ready virtual channels by choosing from a list of common sensors and signals or creating your own custom scale

LabVIEW Integration – All NI-DAQ functions create the waveform data type, which carries acquired data and timing information directly into more than 400 LabVIEW built-in analysis routines for display of results in engineering units on a graph

For information on device support in NI-DAQ 7, visit ni.com/dataacquisition

Visit ni.com/oem ***for quantity discount information.***