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Abstract:

The objectives of this study were to evaluate a novel design dynamic force platform the Quantitative Posturography System (QPS). The evaluation consisted of identifying the effects due to ageing and disease of the postural control system and also to examine the relationship between functional performance and postural sway. An AOVA design and Pearson-Product correlation design were used. Seventy healthy subjects, seven subjects with Parkinson's disease and eight subjects with a history of falls took part in the study. It was found that the QPS was able to identify changes due to both the ageing process and disease on the postural control system. Also a moderate correlation coefficient was found between the sway parameters of the QPS and the two functional balance assessment tests, the Single Leg Stance Test (SLST) and the Functional Reach Test (FR test). In conclusion, the QPS was able to detect the change in the postural control system due to both the ageing process and disease. It was also found that there is a moderately strong relationship between functional performance and postural sway.

Introduction

The maintenance of a person's standing balance is a complex task, requiring their centre of gravity (COG) to remain within their base of support. To maintain balance, the postural control system integrates information from the three sensory systems, through the central nervous system (CNS), which then evokes and controls the co-ordinate muscular responses of the musculoskeletal system (Fransson et al, 1998). As postural control mechanisms deteriorate with age and disease, balance becomes increasingly tenuous resulting in increased susceptibility to falls. Efforts to describe and comprehend balance impairment in older persons have led to the development of several methods of assessing balance. Balance can be assessed at the physiological, functional and disability level. The physiological assessment of balance involves the measurement postural sway directly by tracking the movement of the subject's centre of gravity (COG) or indirectly by tracking the subject's centre of pressure (COP). The subject's COP is an approximation to their COG under static conditions or slow movement. Numerous different types of test equipment have been developed to measure postural sway some of which include: ataxiameters (Wright, 1971), displacement transducers (Fernie et al, 1978), sway magnetometers (Elliott et al, 1998), static force platforms and dynamic force platforms (Prieto et al, 1993; Browne and O'Hare, 2000). The most commonly used technical balance assessment test is a dynamic force platform (Prieto et al, 1993; Hughes et al, 1996). This is due to dynamic force platforms ability to simulate dynamic conditions which require full compensation of the postural control system and thus reveal pathology better than static force platforms or other test equipment which only simulate

static conditions (Furman, 1994; Baloh et al, 1994). Functional Balance can be assessed by functional performance tests such as the Single leg stance test (Gehlsen et al, 1990) and the Functional Reach test (Duncan et al, 1990). However, these tests provide only subjective analysis of functional balance and are not always suitable for monitoring the progression of disease or the efficacy of treatments for particular balance impairments. There have only been a few investigations into the relationship between functional balance and postural sway and the results from these investigations have been conflicting therefore further investigation needs to be carried out.

The system used in this study is a novel design dynamic force platform, the Quantitative Posturography system (QPS), which exaggerates subject's sway and thus challenges the subject's postural control system. This exaggeration of sway is due to the top plate of the QPS being supported by four water bags which compress as the subjects sways and the top plate tilts in the direction of sway and as such is sway referenced exactly to the subject's sway. This has the effect of misleading the proprioceptive system and thus challenging the subject's balance. The objectives of this study were to:
(1) Determine whether this novel design dynamic force platform could differentiate between healthy young subjects and elderly subjects;
(2) Differentiate between healthy subjects and subjects with moderately impaired balance;
(3) Determine if a relationship exists between the sway parameters of the QPS and functional balance, as assessed by two different functional assessment tests.

Methods
Subjects
The healthy subjects consisted of seventy subjects aged between 20 -90 years (sixteen 20 - 30 years' subjects, seventeen 30 - 40 years subjects, eleven 40 - 50 years subjects, six 50 - 60 years subjects, ten 60 - 70 years subjects, five 70 - 80 years subjects and five 80 - 90 years subjects). The healthy subjects were volunteers from the community.
The subjects with impaired balance consisted of eight patients with Parkinson's disease and nine elderly subjects with a history of falls. The subjects were volunteer inpatients or outpatients receiving physical therapy at St. James's Hospital, Dublin.

Design
An analysis of variance and t-test design was used as well as a Pearson-product correlation coefficient design.

Instrumentation
The QPS consists of a top plate, which is supported by four water bags contained within a box of dimensions 50 cm * 50 cm * 11 cm (width*length*height) (Figure 1).   The top plate fits snugly inside the box and therefore there is negligible movement of the top plate over the four water bags. The four water bags were slightly pressurised (60 mmHg) and fixed in place behind retainers. The subject's COP is measured using pressure transducers attached to the water bags, which produce an electrical signal proportional to the applied force. The QPS measures balance indirectly, since it measures a person's COP, which is

then related to their centre of gravity (COG) and ultimately to their balance. This is possible due to the relationship between these three parameters: the movement of a persons centre of gravity is a measure of their balance, and during quiet standing a persons centre of pressure can be approximated to their centre of gravity (Winter, 1995). The subject's COP is calculated from the relative vertical loading of the body weight, beneath the heel and forefoot of each leg. The centre of pressure is calculated from these vertical forces as shown in Figure 2. The COP in the X-direction (ML) and in the Y-direction (AP) are calculated from equations (1) and (2). From the COP measurements the following sway parameters were calculated in both the antero-posterior (AP) and the medio-lateral (ML) directions: root mean square (r.m.s.) displacement, which is the average distance, travelled by the subject's COP;
r.m.s. velocity which is the average speed with which the subject's COP is travelling; and the 95 % confidence ellipse of the area travelled by the subject's COP.

F1=F2=F3=F4=Water bag-transducer unit

$$COP_X = \frac{[F4 - F2] \times [D_{ML}/2]}{[F1 + F2 + F3 + F4]}$$ Equation 1

$$COP_Y = \frac{[F1 - F3] \times [D_{AP}/2]}{[F1 + F2 + F3 + F4]}$$ Equation 2

Procedure and Analysis
Test Procedure
The healthy subjects were screened for suitability before taking part in the study by answering a comprehensive questionnaire to exclude subjects with debilitating cardiac illness, deafness, neurological disease, joint replacement, or vascular disease. While the subjects with a balance impairment were chosen using the following criteria: (1) medical diagnosis of Parkinson's disease or a history of falls; (2) no lower limb deformity; (3) ability to stand independently with no assistive device for 35 seconds; and (4) no cognitive deficits that could interfere with following verbal instructions. The test protocol included being tested firstly by the appropriate functional assessment test and then by the QPS. The healthy subjects were tested with the Single Leg Stance test, which has been advocated as a practical and reliable technique for identifying subjects with normal balance (Gehlsen et al, 1990; Balogun et al, 1994; Potvin et al, 1980; Hanke et al, 1992). The SLST assesses the subject's ability to balance by measuring the length of time they can remain on one foot, the maximum time being 30 seconds. The functional assessment test, which was used to test the two patient groups, was the Functional Reach test (Duncan et al, 1990). It was used to establish the degree of severity with which the patient had the balance impairment. The Functional Reach Test assesses the subject's ability to balance by measuring the distance they are able to reach forward without having to take a step forward. The Single Leg Stance test requires subjects to half their base of

support which would have put the patient groups at risk of falling and was therefore considered unsuitable for evaluating the patient groups. While the Functional Reach test would have been too easy for the healthy volunteers to perform as it only requires subjects to push their COG to the edge of their base of support and would therefore the effect of the ageing process on the postural control system may not have been identified as clearly as with the SLST.

The healthy volunteers and the patients were then instructed to sit quietly for five minutes before commencing the test on the QPS in order to negate any disorientation or fatigue which may have been caused by the functional assessment of balance. A trace of the subjects base of support was made so that, the ratio of the subjects sway area and base of support could be obtained (Hufschmidt et al, 1980; Diener et al, 1984). This trace of the subject's feet was then placed on the top plate of the QPS in the central position, which aligned the subject's COP with the mechanical centre of the top plate. The QPS test involved the subject standing on the system with their feet together for 35 seconds, the subject was asked to look straight ahead, to keep their hands by their sides and to stand as quietly as possible, but not to attention. The first five seconds of the test were not used in the analysis of the COP parameters to allow the subject adjust to the test conditions while the final thirty seconds of the test is the recommended posturography test time by the International Society of Posturography (Kapteyn et al, 1983).

Analysis
Descriptive statistics were used to show the characteristics of the subjects with and without balance impairment. The differences in sway parameters among the healthy subjects of the different age groups were assessed using analysis of variance. While the differences in sway parameters among the age-matched healthy subjects and the two patient groups were assessed using a t-test. Scores on the functional assessment tests, the SLST and the FR test were compared to each of the sway parameters of the QPS using scatterplots and Pearson-product correlation coefficient to assess the strength of the linear relationships.

Results
Calibration of the QPS
The QPS was characterised using a quality control protocol developed and described elsewhere (Browne and O'Hare, 2000). From the calibration it was found that the QPS had a spatial accuracy of between 0.8 - 3mm for a range of loads between 10kg and 80kg. The level of hysteresis found in the system was < 0.2% full scale deflection and a repeatability 0.1% full scale deflection and a temporal stability of 0.5% full scale deflection. Therefore, the QPS was found to be precise and to have acceptable accuracy to measure postural sway (Bizzo et al, 1985).

Normative Data
One of the objectives of this study was to determine whether this novel design dynamic force platform could differentiate between healthy young subjects and elderly subjects.

The means and standard deviations for each of the age groups were calculated. There were no significant differences found in the sway parameters between men and women; therefore, only age-related effects on the sway parameters were focused on. It was found that only two sway parameters of the QPS detected differences between the different age groups, the r.m.s. AP displacement and the r.m.s. AP velocity. These sway parameters increased from 50 years onwards (Figure 3 Figure 4 and Figure 5).

The results from the Single Leg Stance Test (SLST) show a much more obvious decline in the postural control system with increasing age when compared to the QPS (Figure 6).

In general, the regression analysis revealed a moderate negative correlation of $r = -0.5$ between the Single Leg Stance Test and the sway parameters of the QPS for the healthy volunteers.

Patient Data
The subjects in the two patient groups were between 70 and 90 years and they were compared with healthy volunteers of the same age (age-matched healthy volunteers). The means and standard deviations for the two patient groups were calculated. On performing an analysis of variance on the sway parameters for the elderly subjects with a history of falls and the subject's with Parkinson's disease, it was found that they had significantly larger parameters of sway than the age-matched healthy volunteers. The parameter of sway to show the most significant difference between age-matched healthy volunteers and both patient groups was ML displacement ($p < 0.00005$). The results for all parameters of sway, for the elderly subjects with a history of falls and the subjects with Parkinson's disease, and the age matched healthy volunteers are presented in Table 1.

Regression analysis revealed moderate negative correlation $r = -0.6$ between the majority of sway parameters of the QPS and the Functional Reach test results for the elderly subjects with a history of falls and the subjects with Parkinson's disease.

Discussion
Calibration of the QPS
The QPS was found to be precise and to have acceptable accuracy to measure postural sway and the technical specifications for the most part meet the requirements presented by the Association de Francaise de Posturologie (Bizzo et al, 1985).

Normative Data
The increase in the two sway parameters r.m.s. AP displacement and AP velocity indicates that the QPS is sensitive to the changes, which occur due to the ageing process. Many investigators have tried to identify these changes in the postural control system and only a few have been successful (Brocklehurst et al, 1982; Duncan et al, 1992; Blaszczyk et al, 1994; Prieto et al, 1996). Dynamic posturography has been successful in detecting the changes in postural control due to the ageing process and similarly it has been found that the displacement and velocity of sway measurements are most sensitive to the

changes due to the ageing process, both increasing with age (Dornan et al, 1978; Baloh et al, 1994; Furman, 1994; Tell et al, 1998). However, the QPS has a simpler tilting mechanism than conventional dynamic force platforms and also provides a more gradual tilting. Therefore, the QPS would be expected to be safer than conventional dynamic force platforms however this would require further work to be carried out using the QPS to confirm this. It is hypothesised that the QPS will have the same sensitivity as conventional dynamic force platforms for detecting impaired balance but without the stress associated with that of conventional dynamic force platforms.

The more dramatic decline with increasing age in the SLST compared to the QPS may be due to the fact that the two tests assess balance under very different test conditions. The Single Leg Stance Test assesses the subject's balance by reducing the subjects base of support in half and as such reducing their proprioceptive information significantly whereas the QPS only reduces the subject's proprioceptive information by being sway referenced. Therefore, the Single Leg Stance Test stresses the postural control system substantially more than the QPS.

The negative correlation between the QPS sway parameters and the SLST may be due to the following relationship, as the time maintained by the subject decreases there is an increase in the sway parameters of the QPS, indicating a decrease in postural stability. Other investigators have found that measures of postural sway have a weak negative correlation with functional measures of balance made by the non-technical tests (Thapa et al, 1994; Alonte et al, 1995; Hughes et al, 1996). The reason for there only being a moderate correlation between the two tests may be due to the fact that they both are very different types of tests thus, challenging the subjects by different degrees. The SLST is a very challenging test in which, there is a larger reduction in proprioceptive information due to the base of support being halved (single leg stance) as compared to the QPS. Also the QPS measures postural sway while the SLST measures functional balance.

Patient Data
For the most part the results from the two patient groups fell outside of 2 standard deviations of the normal range. This indicates that the QPS has the ability to identify elderly subjects with a history of falls and patients with Parkinson's disease. There were no significant difference found between the two patient groups therefore, the QPS was unable to differentiate between them. This may be due to the small number of patients in each group. The mean values of ML displacement and sway area/BOS for the patients with Parkinson's disease were slightly higher than those for the elderly subject's with a history of falls. This slight difference in ML displacement and sway area/BOS may become statistically significant if larger patient groups are used in future studies and may become a means of differentiating between the two patient groups.

The moderate negative correlation between the Functional Reach Test results and the sway parameters of the QPS may be due to the following relationship between the two tests; the larger the sway parameter then the shorter the subjects reach. Therefore, the larger the sway parameter the greater the instability of the patient and then the greater the impaired function.

In this study the QPS has been found to be successful in identifying changes in the postural control system due to the ageing process and disease. Future studies using the QPS will be to compare its sensitivity to impaired balance with that of a conventional dynamic force platform and also to evaluate larger patient groups to determine sway parameters which, differentiate between the different patient groups.

Conclusions

In this study normative clinical data for the age groups between 20 to 90 years for the QPS was collected. It was found that two sway parameters of the QPS were sensitive to the change in the subject's ability to balance from 50 years onwards, the r.m.s. AP displacement and the r.m.s AP velocity. Furthermore, upon evaluation of the relationship between the sway parameters of the QPS and the functional balance assessment test, the SLST a moderate negative correlation was found.

It was also found that most of the sway parameters of the QPS were sensitive to the elderly subjects with a history of falls and the patients with Parkinson's disease. There were no significant differences found between the two patient groups but this may be due to the size of the patient groups tested and should be further investigated with larger patient groups. Furthermore, a moderate negative correlation between the sway parameters of the QPS and the functional balance assessment test, the Functional Reach Test was found.

In conclusion, a novel way of assessing balance was presented, which has shown to be sensitive to changes in the postural control system, whether they were due to the effects of the age or the presence of a balance disorder. Furthermore, a moderate relationship was found between postural sway and functional balance.

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Table 1: Mean (± 2 standard deviations) of the Age-matched healthy volunteers and the two patient groups, with the probability values of the patient groups belonging to the same population of the age-matched healthy volunteers

Sway Parameter	Age-Matched Healthy Volunteers	Elderly Subjects with a History of Falls	Patients with Parkinson's disease
r.m.s. ML displacement (cm)	0.38 (± 0.02)	0.61 (± 0.1) p<0.05	0.95 (± 0.41) p<0.05
r.m.s. AP displacement (cm)	0.5 (± 0.02)	0.71 (± 0.1) p<0.05	0.71 (± 0.17) p<0.05
r.m.s. ML velocity (cm / sec)	5.5 (±0.21)	6.7 (± 1.0) p<0.05	6.4 (± 2.1) p = 0.07
r.m.s. AP velocity (cm / sec)	6.8 (± 0.35)	8.4 (± 1.4) p<0.05	7.3 (± 2.1) p = 0.41
Sway Area / Base of Support	0.005 (± 0.0008)	0.009 (±0.003) p<0.05	0.01(± 0.001) p<0.05

Figure 1: Quantitative Posturography System

QPS Processing
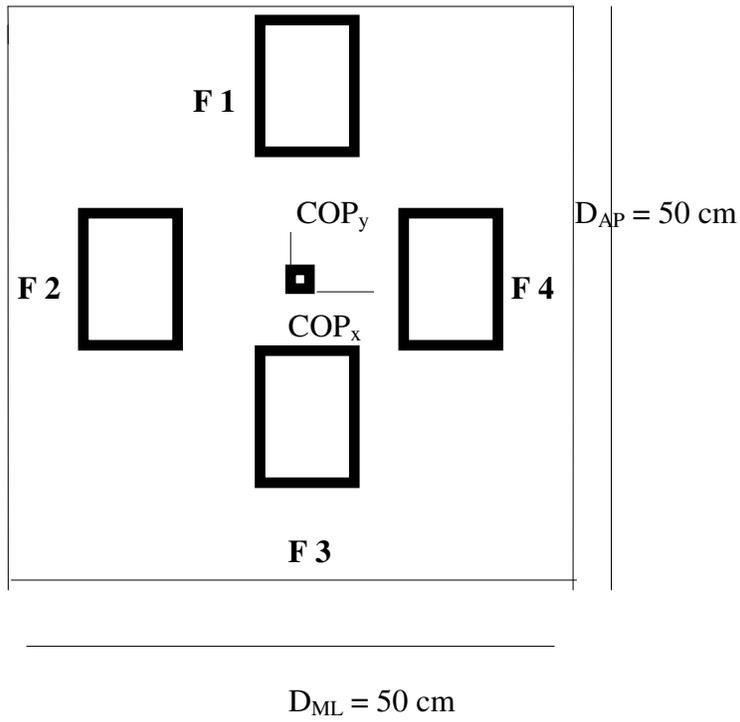and Analysis System

Top Plate

Water bag and Transducer Unit
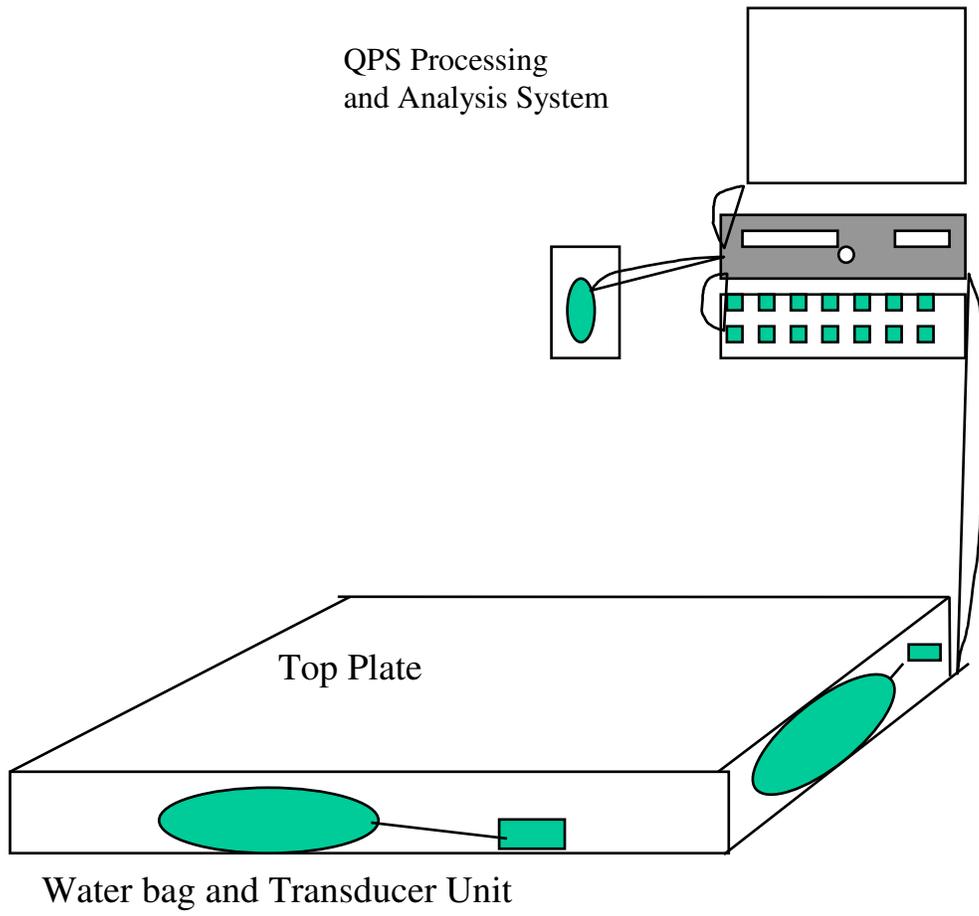
Figure 2: Calculation of the COPx and COPy

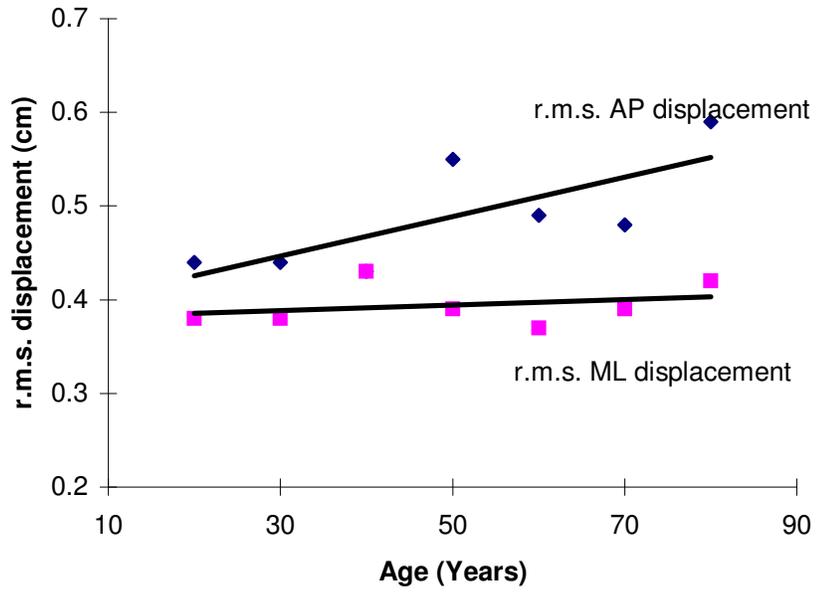**Figure 3: The Relationship between the Sway parameters r.m.s. AP and ML displacement and Age**

Figure 4: The relationship between the Sway parameters r.m.s. AP and ML velocity and Age
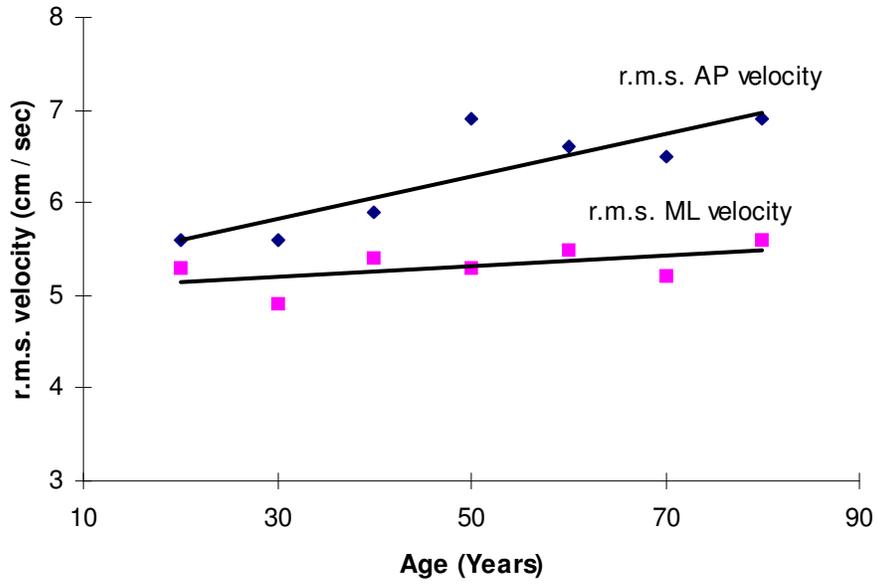
Figure 5: The relationship between the Sway Parameter Sway Area / Base of Support and Age
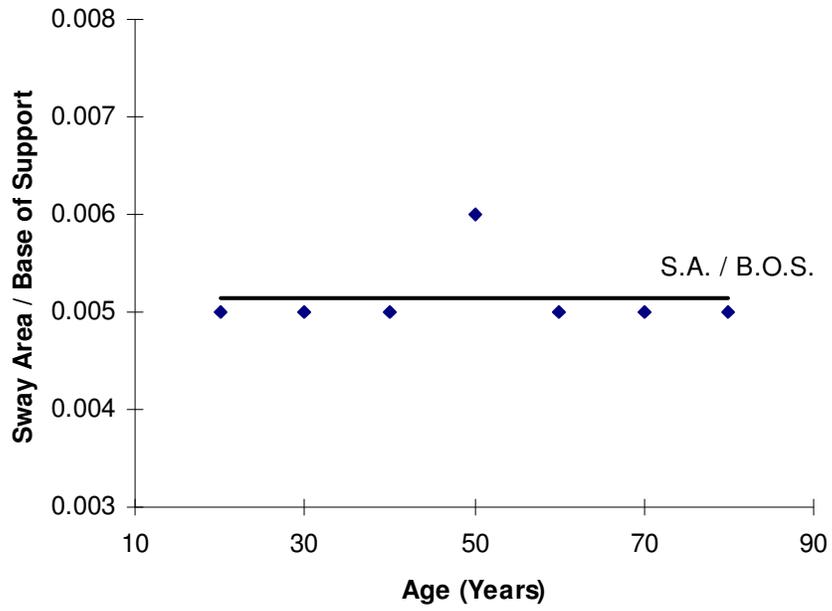
Figure 6: The average time maintained for the SLST by each age group during the eyes open condition