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The Effect of Vision, Muscle Fatigue and Backrest Inclination on the Repositioning Ability of the Cervical spine

By

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A Thesis Submitted for
The Degree of Master of Philosophy

Rehabilitation Engineering Centre
The Hong Kong Polytechnic University

2004

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Abstract of thesis entitled 'The Effect of Vision, Muscle Fatigue and Backrest
Inclination on the Repositioning Ability of the Cervical spine
submitted by Mr. Wong Fu Yan, Thomas
for the degree of Master Of Philosophy
at the Rehabilitation Engineering Centre, The Hong Kong Polytechnic University

Neck pain is prevalent among workers engaged in sedentary work facing a video display unit (VDU) for long periods. Poor working posture has been claimed as one of the possible causes of the pain. Current treatment for postural neck pain is focused mainly on education to improve posture. However, previous studies have not revealed any particular cervical postures that are more highly associated with neck pain than others. Moreover, clinical postural assessment is typically based on a snapshot of the resting head-on-trunk relationship, and does not take dynamic neck postural control into account. The neck postural and movement control system relies on multiple sensory afferent inputs from visual, vestibular and cervical proprioceptive cues. The recent discovery of a region of the cortex which is active in response to incongruence between motor intention, awareness of movement and visual feedback has lead to the hypothesis that disorganized cortical representation of proprioception may falsely signal incongruence between motor intention and movement, resulting in pathological pain.

In this study, the postural control of the cervical spine in terms of active repositioning ability was assessed in normal subjects. Reflective markers were attached to the subjects' head and trunk. Subjects were tested in a Hong Kong Government recommended standard office chair with adjustable backrest tilting angle (Labour Department, 2002). A motion analysis system (Vicon 370, Oxford Metrics, UK) was used to monitor the head position relative to the trunk and to the environment. Initially, subjects were instructed to memorize the starting normal working head posture. Then, this starting position was reproduced after a standardized series of movements. Repositioning ability was calculated as the discrepancy between the repeated position and the memorized starting position. This procedure was repeated for different inclinations of the chair back and with vision either occluded or not. The measurements were also repeated after a fatigue protocol, in which fatigue of both upper trapezius muscles were induced. Repositioning ability of cervical spine was quantified in terms of angular and translational repositioning accuracy (mean error) and precision (variability error) with respect to a local three-dimensional coordinate system defined with respect to the trunk and a global three-dimensional coordinate system defined with respect to the external environment.

Vision was demonstrated to have significant effect on the repositioning precision of the cervical spine in nearly all directions. Interestingly, fatigue of both upper trapezius muscles was found to result in improvement of the angular repositioning precision of the cervical spine in axial rotation but deterioration of translational repositioning accuracy in sidegliding. Tilting of the chair was found to have little effect on angular repositioning accuracy and precision, but did have a significant effect on the translational repositioning accuracy along the vertical axis.

Treatment of postural neck pain by education will be in vain if the clinical assessment of neck posture by obtaining a snapshot of the resting head-on-trunk is inadequate to document the normal function of the postural system. In order to address the deficit of each of the underlying components of postural control, it was concluded that the integrity of the head postural control would be better assessed by differential assessment of repositioning accuracy and precision of the cervical spine.

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INTRODUCTION

The increasing use of computer technology in the workplace means that working habits have also changed, and more people are now engaged in sedentary work facing a video display unit (VDU) for long periods of time. In 1984 only 25 percent of the U.S. population used computers at work, but by 1993 this number had increased to more than 45 percent of the population, and has continued to grow (U.S. Department of Labor, 1997). More than 18 million workers in the USA using computers are also engaged in jobs that often require intensive keyboard use, and clinical observations have revealed a high prevalence of neck pain in these workers (U.S. Department of Labor, 1997). Sustained periods of poor head and shoulder posture have been advocated as one of the contributing factors to the onset and perpetuation of cervical pain syndrome (Kendall et al., 1983).

Patients with postural cervical pain syndrome are usually referred for physiotherapy and treatment regimes, which typically included exercise and instruction for postural correction following postural assessment. Postural assessment usually involves obtaining a snapshot of the patients' neck resting posture and comparing this against the standard neck resting posture of the normal population (Kendall et al. 1983). Unfortunately, there is no standard, reliable and objective tool for measuring head posture in clinic (Grimmer, 1997, Hickey et al. 2000), and moreover it has been shown that subjects with extreme cervical resting postures do not have a significantly higher incidence of neck pain than those in the normal range (Grimmer 1996). Indeed, there is no particular cervical resting posture that is more closely associated with neck pain than other postures (Grimmer, 1997). For the spine to be maintained in a correct posture with minimal biomechanical stress, sufficient afferent information concerning the static joint position must be available (Di Fabio et al. 1997). The orientation of the head in space and with respect to the trunk makes use of multiple sensory afferents, specifically visual, vestibular and cervical proprioceptive cues (Di Fabio et al. 1997). For the maintenance of the head on neck posture, neck proprioceptors detect the orientation of head with respect to the trunk, while the vestibular apparatus and the eyes detect the orientation and movement of the head with respect to gravity and external environment, respectively. It was therefore proposed that the proprioceptive system of the neck plays a predominant role in maintaining the head on neck posture (Revel et al., 1991). As such, it has been suggested that measures of neck proprioception may be a better alternative approach to assessment of postural awareness than the traditional 'snapshot' of the head resting posture. The postural control of the cervical spine in terms of active repositioning ability was assessed in normal subjects by means of lightweight reflective markers attached to the subjects' head and trunk which were used to monitor the head position relative to the trunk and to the external environment. Subjects were instructed to memorize an initial neutral working posture, and then repeat this memorized posture after a standardized series of neck and head movements. Repositioning ability was calculated as the discrepancy between the memorized and the repeated position. This procedure was repeated for different chairback inclinations (upright, backward and forward) and different visual conditions (eyes open or closed). Results were obtained both before and after fatigue of the upper trapezius muscles.

BACKGROUND

2.1 Postural and movement control

Posture is defined as a neuromechanical response that concerns the maintenance of equilibrium (Enoka, 1994). This maintenance of equilibrium is required for stability during motion of the body or limbs. Control of posture is an adaptable feature of the motor system and depends on the integration of both afferent input and efferent output (Enoka, 1994), rather than being based on a set of reflex responses or a pre-programmed response to a disturbance. The afferent input acts as a feedback of movement control, and is mediated through exteroception (sensations from the external environment, e.g., tactile sensation) and proprioception. Proprioception concerns the physical state of the body, including position sense, tendon and muscle status and even the state of equilibrium, which is generally considered to be a 'special' or 'sixth' sense rather than ordinary somatic sense (Guyton 1986, Parkhurst and Burnett, 1994).

2.2 Proprioception

The term proprioception was derived by Sherrington (1906) from the Latin *proprius* to refer to perception of sensations that originate in receptors that are stimulated by an organism's own movement. Although the word 'proprioceptor' is obsolete and inaccurate according to a commentary of the Journal of Manipulative and Physiological Therapeutics (Seaman, 1997), there is still considerable debate among neurologists on whether proprioceptors should be considered as a category of receptors. For the purposes of this study, the author refers to the neck proprioceptors as the muscle spindles, golgi tendon organs and joint receptors of the neck. The muscle spindles are responsible for monitoring the muscle length and rate of change of length while the golgi tendon organs are responsible for monitoring the muscle tension and rate of change of tension. The function of the joint receptors is to monitor the position, displacement, velocity and acceleration of movement and noxious stimuli (Guyton, 1986).

For maintenance of the head on neck posture, the neck proprioceptors detect the orientation of the head with respect to the trunk, while the exteroceptors of the vestibular apparatus and eyes detect the orientation and movements of the head alone. These exteroceptors and proprioceptors work together closely, and their relationship is clearly illustrated by the fact that the proprioceptive information of the orientation of head with respect to trunk is send directly into vestibular and reticular nuclei of brain stem and also indirectly by way of the cerebellum (Guyton, 1986).

Traditionally, the term position sense is subdivided into two types, namely static position sense and kinesthetic sense. Static position sense refers to the conscious recognition of the orientation of the different parts of the body with respect to each other while kinesthetic sense refers to recognition of the rate of movement of the different parts of the body (Guyton, 1986). Resting posture is only a state of equilibrium related to static position sense. However, both static and dynamic position sense in general are based on integrated inputs from the somatosensory, vestibular and visual systems, and compromise of any of these may affect the overall position sense. As such, assessment of postural control should reflect this, and ideally provide information on each of the three systems involved in postural control. Simply obtaining a snapshot of the resting posture of the neck and comparing it against a standard is insufficient to do this.

2.3 Measurement of spinal proprioception

There are three objective ways to measure spinal proprioception (Parkhurst and Burnett, 1994), namely passive motion threshold, directional motion perception and repositioning accuracy. Passive motion threshold is a measure of the smallest motion a subject can perceive in a given plane and direction of movement during passive movement. Directional motion perception also involves passive movement, but the subject is not informed of the direction of movement. The directional motion perception is determined by the subject's stated perception of the direction of motion during the test. The total score for a given plane of movement is assessed as a percentage of correct answers out of the total number of trials. The method of repositioning accuracy involves asking the subject to accurately reposition a body part to a predetermined position. The deviation of the repeated position from the original position is recorded as the repositioning accuracy, such that the best possible score for repositioning accuracy is zero.

Taylor and McCloskey (1988) used the passive motion technique to assess neck proprioception. Subjects were blindfolded with the head fixed tightly to an external frame, and were seated in a motor driven chair that could be rotated at angular velocities from 0.07° to 5.7°/s. The subjects were asked to determine when they could perceive the passive rotation of the body with respect to the head for at least three rotation velocities. The maximum passive motion threshold was found to be 1.4° at the slowest angular testing speed of 0.1°/sec. However, it was found that the threshold was significantly lower when the head was turned with respect to a stationary lower body than vice versa. The authors also reported technical difficulties in determining a reliable lower limit for the crossover line at fast testing speeds (i.e. an excursion at which the direction of motion could never be identified). In other words, the slower the testing speed, the larger the angular excursion and the easier it was to obtain reliable results.

Owing to the slow testing speed and large number of repetitions required, the passive motion threshold method is particularly time demanding, whereas the repositioning accuracy method is the least time consuming among the three methods of assessment of proprioception. Later, a threshold hunting paradigm was proposed by Weiler and Awiszus (1998), which allowed the subjects to change the parameter value (i.e. testing velocity) continuously around the threshold producing a threshold hunting curve, and is claimed to reduce the time required to conduct passive motion threshold assessment. Nevertheless, the repositioning accuracy method has the additional advantage that the motion is produced actively by the subject, and there is less risk of damage to the tissues than when the motion is produced by an externally applied force.

2.3.1 Active and passive repositioning

Voluntary movement involves central command generated from the motor cortex to the lower neural centers like brainstem and then back to supraspinal centers (Enoka, 2002). The corollary discharge that is transferred back is a copy of efferent signals, and is sometimes called efferent copy. Active repositioning involves a certain degree of feed-forward motor control, in which additional information is given by the efferent feedback (Bosco and Poppele 2001). For the perception of joint position, the afferent signals from muscle, articular, tendon, and skin receptors deliver relative information for central processing only, while the efferent copy acting as reference point (Fel'dman and Latash, 1982). This reference point (i.e. efferent copy) will probably shift during voluntary regulation state due to muscle contractions, but remains unchanged during any passive alternations of joint position (Fel'dman and Latash 1982).

The effect of the efferent copy being considered is the main difference between active and passive repositioning, and is illustrated in a study by Jakobs et al. (1985), who examined the repositioning accuracy of the trunk in the frontal plane. Twenty healthy subjects were tested for their ability to center the first thoracic vetebra (T1) over the first sacral vertebra (S1) in standing and lying positions with vision occluded and the pelvis immobilized. The subject either actively moved or was moved passively from side to side in lateral bending for 20s at a speed of 5cm/s, giving a maximum displacement of 10cm. The subject was asked to report the moment when T1 was aligned with S1 along the superior-inferior axis, and the mean offset was measured as the trunk repositioning accuracy in the frontal plane. The mean error was found to be 3.1mm (standard deviation 1.7mm) or 0.3° (standard deviation 0.3°) in relaxed standing tests, and 8.8 mm (standard deviation 3.3mm) or 0.9° (standard deviation 0.7°) in supine tests. While the trunk repositioning accuracy was found to be significantly poorer in the supine position than the standing position, results showed that repositioning accuracy was independent of whether the subject was moved actively or passively. No significant difference between active and passive repositioning accuracy was found for trunk motion.

No direct comparisons of active and passive repositioning accuracy could be found for cervical spinal motion, although some information is provided in a study conducted by Taylor and McCloskey (1988). Subjects were asked to indicate the direction of the fixed right hallux by turning the head to face the same direction while blindfolded. The angular deviation between the head and right hallux angles was recorded as the accuracy. This active repositioning task was achieved by activation of the neck muscles, and was also compared to repositioning via a hoop handrail surrounding the chair, and passive repositioning using a motor drive to rotate the chair. Obviously, active repositioning by turning the head involved efferent copy by the active use of the muscles in neck, which was not the case in the other two situations. Results showed the mean undershoot when turning the head was 1.7° (standard error 1.0°), as compared to 3.0° (standard error 2.4°) for passive repositioning to the fixed head using the seat motor and 3.0° (standard error 1.7°) by pulling on the hoop. The repositioning accuracy when turning the head to target the fixed hallux was not significantly better than the other two conditions. However, due to the unclear role of vestibular input (which was included in the active repositioning but not in passive repositioning), Taylor and McCloskey did not go so far as to conclusively state that the active and passive repositioning accuracies are the same (Taylor and McCloskey, 1988).

While there may be some difference between passive and active repositioning accuracy in the cervical spine, most studies evaluating neck proprioception have used active repositioning as the basis of assessment, as outlined in the following section.

2.4 Proprioception and neck pain

Revel et al. (1991) found that the cervicocephalic kinesthetic sensibility (in terms of repositioning ability) of the head was significantly poorer in thirty neck pain patients than thirty healthy subjects. All subjects wore a helmet with a light beam attached and a pair of goggles to occlude vision. Subjects were asked to maintain and memorize an initial relaxed posture facing directly ahead and a target board 90cm in front of the subjects was centred on the light beam. The subjects were than asked to perform near maximal left rotation of the head and hold this position for 2 seconds before returning to the initial position, without any limitation placed on speed of rotation. The position of the light beam was marked on the target, and the deviation from the target centre recorded as the global error. The horizontal and vertical repositioning errors were measured against the abscissa and ordinate axes respectively, and the centrimetric measurements converted to angles with the light source as the centre of rotation. Each component was assigned a positive or negative sign according to its position below or above zero on the corresponding axis.

This process was repeated 10 times for head motion in each of left rotation, right rotation, flexion and extension, with the head repositioned at the initial position (light beam at the target centre) between trials. Results indicated a significantly poorer repositioning accuracy in the patient group, with mean repositioning errors of 6.11° horizontally and 5.47° vertically, as compared to respective errors of 3.50° and 3.37° in the normal subjects. On the basis of these results, Revel et al. (1991) suggested that a threshold error of 4.5° would discriminate normal subjects from cervical pain patients with a sensitivity of 86% and specificity of 93%.

A Swedish study was later conducted using a similar technique with fourteen whiplash injury patients and thirty-four healthy subjects (Heikkila and Astrom 1996). The experimental arrangement and methodology was identical to that used by Revel et al. (1991), but centrimetric measurements taken from the target board were reported without conversion into angles. The mean error for the whiplash patient group was 4.2cm (standard deviation 2.93cm) for horizontal repositioning and 5.2cm (standard deviation 3.52cm) for vertical repositioning, as compared to a mean global error of 2.7cm (standard deviation 0.81cm) in the normal subject group. A significantly poorer cervicocephalic kinesthetic sensibility (in terms of repositioning ability) was therefore demonstrated in whiplash patients. The same group later reported similar results from an identical study using larger subject groups of twenty-seven patients with whiplash injury and thirty-nine healthy subjects (Heikkila and Wenngren 1998). A mean overall relocation error of 3.84cm (standard deviation 3.2cm) was found in the whiplash subject group as compared to 2.75cm (standard deviation 1.9cm) in the normal subjects.

Loudon et al. (1997) compared the repositioning ability of whiplash patients and normal subjects using a cervical range-of-motion device to monitor head motion in three cardinal planes instead of the simplified 2-dimensional representation used previously (Revel et al. 1991, Heikkila and Astrom 1996, Heikkila and Wenngren 1998). Subjects were asked to reproduce six passively placed criterion positions of 30^o and 50^o right and left rotation, and 20^o right and left side bending. The whiplash group showed an average absolute repositioning error of 5.01^o, which was significantly higher than that achieved by the control group (1.75^o).

A recent study (Rix and Bagust, 2001) conducted using the same technique as Revel (1991) found that eleven nontraumatic neck pain patients did not show significantly poorer repositioning ability than a control group of eleven normal subjects in any of the direction except flexion. However, no whiplash patients were included in this study, and the origin of the chronic cervical pain was not controlled. The authors also commented that the results might have limited clinical meaning due to the indistinct separation of the data on scatterplots (Rix and Bagust, 2001).

In summary, all except one of the studies outlined above showed a consistently poorer cervicocephalic kinesthetic sensibility (in terms of repositioning ability) in patients with neck pain or whiplash injury. However, nearly all of the previous studies of the proprioception of the neck were measured indirectly in terms of the repositioning ability of the head in space rather than that of the head on the trunk.

The rationale of these experiments was based on the assumption that the repositioning accuracy of the head in space is identical to the repositioning accuracy of the head on the trunk and that neck proprioception contributed more to the head repositioning vestibular input (Taylor and McCloskey, 1988). From the physiological point of view, the otolith organs of the vestibular system are also responsible for providing tonic information about the position of the head in space, by virtue of its reaction to the constant gravitational force (Guyton, 1986). The contribution of the vestibular system and its interaction with neck proprioception was not clearly stated in the original study by Taylor and McCloskey (1988), and in view of this, similar studies of reproduction accuracy in the lumbar spine were also reviewed.

2.5 Proprioception and low back pain

Lower back proprioception as defined by repositioning accuracy, passive motion threshold and directional motion perception of eighty-eight firefighters using a self-designed spinal motion apparatus was reported by Parkhurst & Burnett (1994). Visually occluded subjects were initially placed in a position approximately 5° from the neutral position for 5 seconds. The subject was then moved to the neutral position and was asked to return to the original position. The average repositioning accuracy in the coronal, sagittal and transverse planes were 1.02°, 1.165° and 0.825° respectively. Measures of the repositioning accuracy in all three planes were neither statistically correlated with longevity factors (age and years of fire-fighting experience) nor history of injury.

Gill & Callaghan (1998) investigated proprioception in twenty low back pain (LBP) patients and a control group of twenty pain-free subjects using a lumbar motion monitor. Blindfolded subjects were required to reproduce a predetermined target position while standing and in four point kneeling. The mean errors of repositioning ability of the LBP patient group in standing and four point kneeling were 6.7° (standard deviation 5.0°) and 8.1° (standard deviation 3.9°) respectively, while the results for the control group were 4.5° (standard deviation 3.4°) and 5.6° (standard deviation 4.7°) respectively. A significant difference in repositioning accuracy was found between the LBP group and the pain-free control group both in standing and kneeling, indicating the presence of spinal proprioceptive deficits in LBP patients.

A recent study (Newcomer et al., 2000a) found no significant differences in repositioning error between twenty subjects with chronic LBP and twenty control subjects. A 3Space Tracker was used which measured three-dimensional position in space with electromagnetic sensors. Subjects were asked to reproduce six actively placed criterion positions which consisted of 50% of the maximum ranges of motion in flexion, extension, right and left lateral bending and right and left rotation. Results showed no significant differences in repositioning error between the LBP group and the control group in any trunk direction. However, a similar study by the same group later the same year (Newcomer et al., 2000b) did indicate significant differences in repositioning error between twenty subjects with chronic low back pain and twenty control subjects. The experiment was carried out in similar fashion to the original experiment (Newcomer et al. 2000a), but with restricted movement of the lower extremities and pelvis. Subjects were asked to reproduced three actively placed criterion position in three positions along four directions (30%, 60% and 90% of the maximum range of motion in flexion, extension, right lateral bending and left lateral bending) with their eyes closed. Significant differences in repositioning error were observed between the LBP and the control group, with the LBP group showing a higher repositioning error in flexion, but a lower repositioning error in extension.

Overall, results regarding low back pain and proproception (in terms of repositioning accuracy) are inconsistent. This may be partly due to the differences in experimental approach, but may also be due to the fact that the relationship between proprioception and pain may be very subtle, if it exists at all. A more sensitive methodology may be required to detect any such relationship.

2.6 Repositioning accuracy

Most of the documented studies on repositioning error have used a 'projection method' based on the original paper by Revel et al. (Revel et al. 1991, Revel et al. 1994, Heikkila and Astrom 1996, Heikkila and Wenngren 1998, Rix and Bagust 2001). Loudon et al. (1997) monitored the head motion in three cardinal planes instead of the 2-dimensional representation used in the projection method, while Christensen and Nilsson (1999) used an electrogoniometric method which allowed measurement of the head on trunk relationship. A CA-6000 spine motion analyzer was used, which consisted of high precision potentiometers linked by a series of bars to a headpiece and shoulder strap. Thirty-eight asymptomatic subjects were seated in a chair with adjustable handles, and asked to position their head in a subjective neutral position with eyes closed. After recording the neutral position subjects were asked to move their head in all six directions (flexion, extension, left and right lateral bending and left and right rotation) for five seconds before returning to the neutral position. The absolute angular deviation from neutral zero for 3 repeat trials was found to be 2.7° in the sagittal plane (standard deviation 2.1°), 1.0° in the transverse plane (standard deviation 0.85°), and 0.65° (standard deviation 0.67°) in the coronal plane.

Each of these techniques has associated advantages and limitations that need to be considered carefully. The following sections outline the most important general and specific limitations in measurement of repositioning accuracy.

2.6.1 Contact and non-contact methods

All of the methods described (Revel et al. 1991, Revel et al. 1994, Heikkila and Astrom 1996, Loudon et al. 1997, Heikkila and Wenngren 1998, Christensen et al. 1999, Rix and Bagust 2001) used a contact measurement method to some extent, where cutaneous mechanoreceptors would be stimulated via skin contact and stretching. Ideally, the skin contact should be kept to a minimum to reduce the extracutaneous afferent input, and the extra loading of the head due to helmet and goggles (amounting to 287g; Revel et al. 1991) avoided if possible, as this may also interfere with the sensory repositioning ability.

2.6.2 Two-dimensional and three-dimensional methods

The motion of the head can be represented in terms of translation and rotation about three orthogonal axes, giving six possible degrees of freedom. The projection method originally outlined by Revel et al. (1991) distills this motion into a 2-dimensional representation by projecting a line from the head onto the coronal plane. However, the same projected point on this plane does not necessarily represent a unique head position in space. For example, any translational motion directly along the line of projection (protraction) will not cause any shift in the position of the projected point on the target. Protracted head posture is considered to be a combination of end range of extension of the Occipit-C1 and C1-C2 upper cervical joints and flattening of the lower cervical spine (Ordway et al., 1999), and therefore the biomechanical stresses in the cervical spine will alter with protraction.

By and large, the complex compensation and overcompensation interaction of angular and translational errors associated with the projection method make the results difficult to interpret, and a degree of experimenter bias and geometric inaccuracy is also inevitably involved in this technique (Rix and Bagust, 2001).

2.6.3 Head in space and head on trunk

There are three frames of reference for postural control, namely the egocentric, exocentric and geocentric reference systems (Di Frabio and Emasithi 1997). The egocentric reference system concerns the relative spatial orientations of the body segments (e.g. head on trunk relationship), the exocentric reference frame concerns body position with respect to the environment, and the geocentric reference system is related to maintenance of posture with respect to the gravitational field. For the maintenance of head on neck posture, neck proprioceptors detect the orientation of the head with respect to the trunk, while the vestibular apparatus and eyes detect the orientation and movements of the head independent of the trunk. Differential assessment of repositioning accuracy of both the head in space (geocentric and exocentric reference systems) and the head on trunk (egocentric reference system) should be therefore be addressed in order to determine the importance of each of these components in relation to the complete postural control system.

Most of the reviewed studies have studied the head in space repositioning accuracy rather than the head on trunk repositioning accuracy (Revel et al. 1991, Revel et al. 1994, Heikkila and Astrom 1996, Heikkila and Wenngren 1998), but two major assumptions have been made in these cases. The first assumption is that the head in space repositioning accuracy is exactly equal to the head on trunk repositioning accuracy, which is only true if the trunk is completely restrained in a gravitational reference position, i.e., there is no trunk in space motion. The second assumption is that neck proprioception contributes more to positioning of the head in relation to a target than vestibular input (Taylor and McCloskey, 1988).

Taylor and McCloskey (1988) found that repositioning accuracy with the availability of vestibular input was not significantly better than without vestibular input, and therefore concluded that neck proprioception overshadows the role of vestibular input in repositioning. However, this may be an over-generalization as the vestibular input may play a greater role in accurate positioning of the head in other planes (Taylor and McCloskey, 1988). From the physiological point of view, the otolith organs of the vestibular system are also responsible for providing tonic information about the head in space position, by virtue of reaction to the constant gravitational force (Guyton, 1986). The interaction of the vestibular system was not clearly stated in the study by Taylor and McCloskey (1988).

2.6.4 Plane of motion

In the vestibular system, the macula of the utricle plays an important role in determining the normal orientation of the head with respect to the direction of gravitational or acceleratory forces (Guyton, 1986). The macula of the saccule operates similarly but is orthogonally aligned. In reaction to the constant gravitational force, both organs transmit tonic information about the position of the head in space as well as linear acceleration due to changes in gravity, acceleration and deceleration of movement or tilting of the head (Guyton, 1986). Owing to the complex organization of hair cell clusters in the utricle and saccule, a tilt of the head in any direction will activate the subpopulation of hair cells that has a corresponding axis of polarity, inhibit those with opposite polarity, and have no effect on those that are orthogonally aligned. These sets of signals from the utricle and saccule help to continuously monitor the head-in-space position (Guyton, 1986). However, the vestibular input may play a lesser role in accurate positioning of the head in the frontal (i.e. coronal) plane as the otholiths are sensitive to changes along the orientation of gravity only (Taylor and McCloskey, 1988). By the same token, the contribution of vestibular input in translational components of the repositioning accuracy of the steady state of the head is questionable.

2.6.5 Speed of active movement

When the head is turned, the inertia of the fluid in the semicircular canals generates a force again the stereocilia, causing them to bend (Guyton, 1986). In the vestibular system, the three pairs of semicircular canals are orthogonally oriented with respect to each other, with matched pairs on either side of the head. By comparing the signals from all three pairs of canals, precise head position can be computed. However, it must be stressed that the semicircular canals detect changes in angular acceleration only and do not supply steady state head in space position information (Guyton, 1986).

During the assessment of repositioning accuracy, the speed of active movement should be controlled, such that sufficient time is allowed for the repositioned head to reach a steady state before the repositioning error is measured, such that the effects of the semicircular canals do not influence the outcome.

2.6.6 Range of active movement

In Rix and Bagust's study of cervicocephalic kinesthetic sensibility in patients with chronic and non-traumatic cervical spine pain, subjects were asked to perform a near maximal rather than maximal movement of the head (Rix and Bagust, 2001). The rationale was that most of the neck pain subjects experienced a sharp increase in pain at the end range of movement, which may possibly affect their repositioning ability

(Rix and Bagust, 2001). Although the present study involves normal subjects only, near maximal movement is still preferred for better comparison with other studies.

2.6.7 Effects of number of trials

Repositioning ability of the cervical spine was quantified in terms of angular and translational repositioning accuracy (Mean Error) and precision (Variability Error). The stability of these derived variables is largely dependent on the number of trials used (Allison and Fukushima, 2003). From the previous studies, the number of trials used ranged from 3 to 10. In real practice, the lesser the number of trials, the more feasible the test will be in clinical practice if patients are involved. Therefore, in the pilot study, the effect of number of trials was studied in five subjects. Each subject was asked to memorize an initial neutral posture with eyes closed seated in a testing chair with upright backrest, and then instructed to perform near maximal cervical flexion, extension, right rotation, left rotation, right side flexion and left side flexion in that order before returning the head to the memorized posture. This process of sequential motion and reproduction of the memorized position was repeated 10 times, such that 10 repeats of the memorized position were recorded. Repositioning error was calculated based on the angular difference between the memorized and the reproduced posture. Standard Error of angular repositioning errors in flexion, lateral flexion and axial rotation were obtained with results plotted against number of trials involved (Fig 2.1, Fig 2.2 & Fig 2.3). By deriving the standard error from increasing number of trials, the data stabilized at a steady value after six trials. The results obtained were also comparable to findings in lumbar spine.

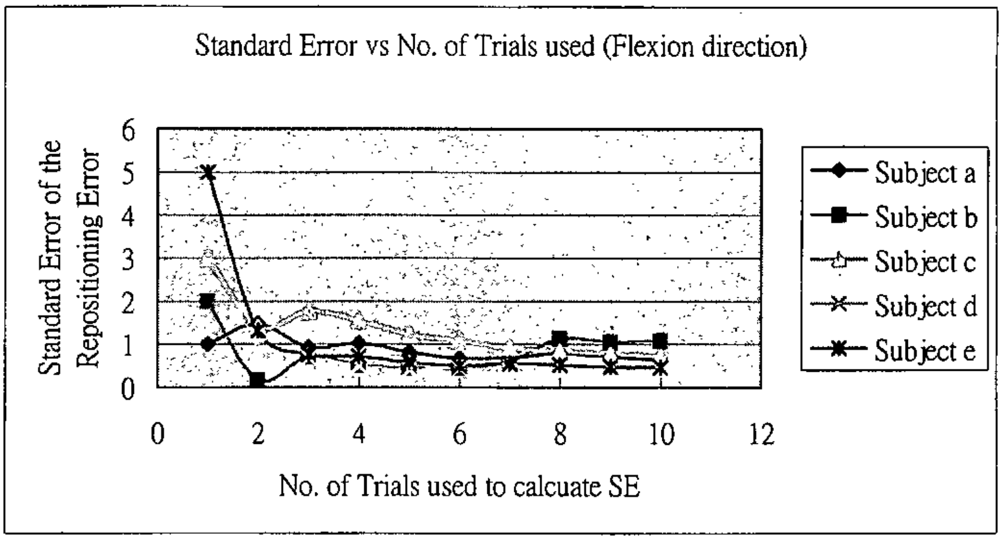


Fig.2.1. Standard error (SE) of the angular repositioning error in flexion plotted against the number of trials used to derive the SE

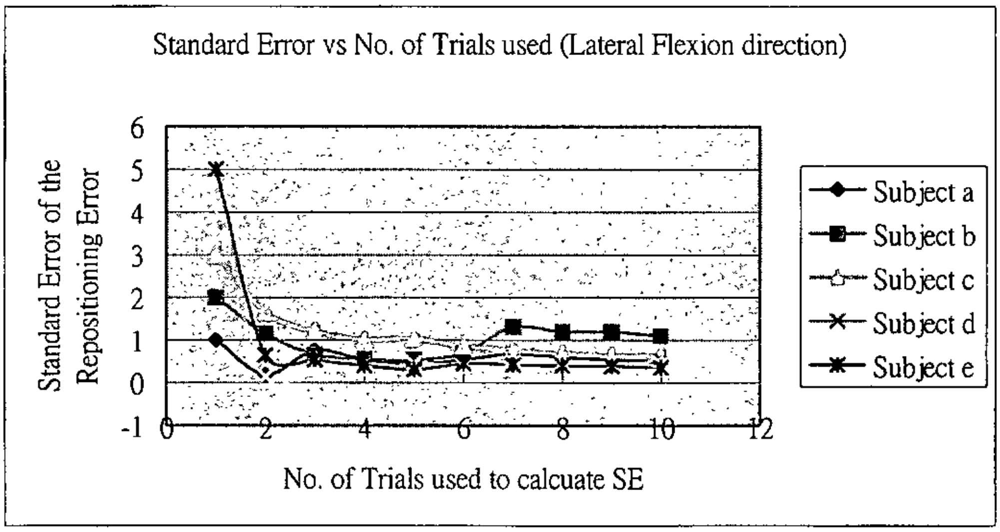


Fig.2.2. Standard error (SE) of the angular repositioning error in lateral flexion plotted against the number of trials used to derive the SE

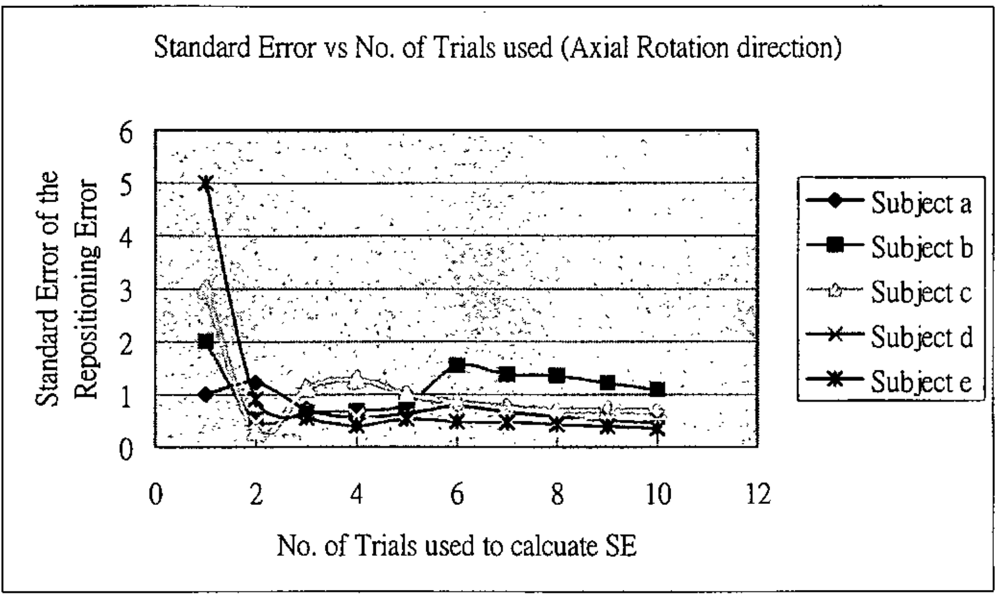


Fig.2.3. Standard error (SE) of the angular repositioning error in axial rotation plotted against the number of trials used to derive the SE

Table 2.1. Methodological details of previous studies assessing accuracy of neck repositioning

Authors	Contact/ non-contact	2D/ 3D	Head-in-space/ trunk	Active/ passive repositioning	Plane of motion	Speed of active movement	Range of active movement	Criterion/ neutral position	No. Of trials
Taylor and McCloskey, 1988	Contact	2D	Head-in-space	Active + passive	Horizontal	NS	NS	Criterion	10
Revel et al., 1991	Semi-contact	2D	Head-in-space	Active	Horizontal + Vertical	No instruction	Maximal	Relaxed position	10
Revel et al., 1994	Semi-contact	2D	Head-in-space	Active	Horizontal + Vertical	No instruction	Maximal	Relaxed position	10
Heikkila and Astrom, 1996	Semi-contact	2D	Head-in-space	Active	Horizontal + Vertical	NS	Maximal	Relaxed position	10
Loudon et al., 1997	Semi-contact	3D	Head-in-space	Active	Sagittal, Frontal, Transverse	Controlled	NS	Criterion	3
Heikkila and Wenngren, 1998	Semi-contact	2D	Head-in-space	Active	Horizontal + Vertical	NS	Maximal	Relaxed position	10
Christensen and Nilsson, 1999	Contact	3D	Head-on-trunk	Active	Sagittal, Frontal, Transverse	Controlled	NS	Neutral	3
Rix and Bagust et al., 2001	Semi-contact	2D	Head-in-space	Active	Horizontal + Vertical	NS	Near Maximal	Neutral	10

* NS = Not Specified

The published results are summarized in the following table for reference.

Publication	**Patient group**	**Normal / control group**
Taylor and McCloskey (1988)		1.7° (SEM=1.0°) (Active head turn) 3° (SEM=2.4°) (Passive trunk turn) 3° (SEM=1.7°) (Active trunk turn)
Revel et al. (1991)	6.11° (SD=1.59°) (Horizontal) 5.47° (SD=1.75°) (Vertical)	3.5° (SD=0.82°) (Horizontal) 3.37° (SD=0.73°) (Vertical)
Revel et al. (1994)	7.5° (SD=3.7°) (Pre-Rx) 5.5° (SD=2.6°) (Post-Rx)	7.9° (SD=3°) (Pre-Rx) 7.9° (SD=2.1°) (Post-Rx)
Heikkila and Astrom (1996)	4.2cm (SD=2.93cm) (Horizontal) 5.2cm (SD=3.52cm) (Vertical)	2.7cm (SD=0.81cm) (Global)
Loudon et al. (1997)	5.01° (SD=?)	1.75° (SD=?)
Heikkila and Wenngren (1998)	0.07cm (SD=?) (Horizontal) -0.74cm (SD=?) (Vertical)	-0.06cm (SD=?) (Horizontal) 0.17cm (SD=0.73cm) (Vertical)
Christensen and Nilsson (1999)		2.7° (SD=2.1°) (Sagittal) 1.0° (SD=0.85°) (Horizontal) 0.65° (SD=0.67°) (Frontal)
Rix and Bagust (2001)	2.68° (SD=?) (Horizontal) 3.78° (SD=?) (Vertical)	2.88° (SD=?) (Horizontal) 3.23° (SD=?) (Vertical)

Table 2.2. Results of previous studies on neck repositioning accuracy. Standard deviations (SD) and standard errors of measure (SEM) are quoted where given.

2.7 Fatigue and neck posture

From the biomechanical point of view, the head is inherently unstable as it has a very narrow base of support (the cervical spine). As such, stresses generated in the active and passive tissues of the neck are required to maintain the head in a stable posture, and poor head on neck posture may therefore induce excessive abnormal stresses in the cervical spine. For instance, a head forward posture may induce sustained loading on the neck extensor muscles, as well as compression and anterior shearing forces in the cervical vertebral column. Prolonged mechanical stress due to poor posture may eventually lead to neck pain.

The stability of the head and neck relies mainly on ligamentous and muscular support. Some neck muscles such as the upper trapezius and sternocleidomastoid have a synergistic relationship providing a stabilizing effect, and these together with the investing fascia form a muscle-fascia "collar" which almost completely embraces the neck (Porterfield, 1995). Constant isometric contraction of neck extensors including the upper trapezius are required to hold the head in space against gravity when in a typical VDU working position. Prolonged isometric contraction of the upper trapezius muscle will lead to early fatigue and thus affect the stabilization of the cervical spine. The cervical joint position sense is also based on multiple afferent inputs including muscle spindles. If the fatigue of the upper trapezius does affect the postural awareness of the neck, then neck posture may deteriorate. This is likely to increase fatigue and lead to a degenerative cycle, maybe leading to the development of neck pain.

Neuromuscular fatigue is defined as an inability of a muscle or group of muscles to sustain the required or expected force (Bigland-Ritchie and Woods, 1984). When a muscle contracts, the intramuscular pressure rises, and if this increases beyond a critical level, it causes a progressive restriction of blood flow and thus limits the rate of energy supply. The fatigue threshold corresponds with the onset of limitation of blood flow. For control of posture, the neck muscles are required to sustain isometric contraction, and patients with postural cervical pain syndromes usually report symptoms after sustaining a posture for a prolonged period of time. Poor cervical posture is often associated with increase in load on antigravity cervical structures. Sustained isometric contraction of cervical muscles with increase in loading may lead to early fatigue.

Previously, it was believed that position and kinesthetic sense were attributable to joint receptors rather than muscle receptors. In other words, joint angle sensation was thought to result from the central processing of information from joint receptors that specifically encode joint angle. However it is now clear that muscle spindles, besides being muscle length monitors, are also major contributors to the kinesthetic sense of position and movement (Bosco and Poppele, 2001). Therefore muscular fatigue is now thought to be one of the factors influencing the proprioceptive function (Bigland-Ritchie and Woods, 1984). Without adequate afferent information, it will be more difficult to maintain good posture, and deterioration in posture is likely to result in pain due to faulty alignment causing undue pressure on articulating surfaces and undue tensions on ligaments (Kendall et al., 1983). The cumulative effects of these constant or repeated small stresses over a long period of time may give rise to chronic pain symptoms.

2.7.1 Fatigue and proprioception in peripheral joints

From the results of the study by Clark et al. (1986), a reduction in position sense in the metacarpophalangeal joint of the finger was found after anesthesia was administered to the interosseous muscle. Gandevia and McCloskey (1978) also found that there was a deficit in movement sense after surgical removal of the musculature around the distal interphalangeal joint in the finger. These findings suggest that there might be some activation overlapping between the articular and musculature mechanoreceptors. A study by Carpenter et al. (1998) investigated the effect of muscle fatigue on shoulder joint proprioception in twenty healthy volunteers. The proprioception of the shoulder was tested by measuring the threshold of detection of humeral rotation with the joint at 90^o abduction and 90^o external rotation, before and after fatiguing exercise by an isokinetic machine. Results revealed significant deterioration ($p<0.001$) of joint position sense with the detection threshold increasing from 0.92^o (standard deviation 0.2^o) before fatigue to 1.59^o (standard deviation 0.59^o) after fatigue.

2.7.2 Fatigue and proprioception in spinal joints

A Finnish study (Taimela et al., 1999) investigated the effect of lumbar fatigue on the ability to sense a change in lumbar position. In their study, 106 subjects (57 patients with low back trouble and 49 healthy control subjects) were assessed in terms of their ability to sense a change in lumbar position while seated on a special trunk rotation unit, before and after performing an endurance task. The angular velocity of the rotating chair was 1 degree per second in the sagittal plane, similar to the value of 0.6 degree per second used in a previous study in the US (Parkhurst and Burnett, 1994). During the fatiguing task, the subjects were asked to repeat upper trunk extensions against a resistance between 25^o flexion and 5^o extension, until exhaustion. Proprioception was impaired significantly by fatigue among patients and control subjects, and the impairment was noted to be more severe among patient than among controls. While some data exists for the lumbar spine, no studies providing direct evidence of the effect of fatigue on the proprioception of the cervical spine could be found.

2.8 Vision and posture

Newcomer et al. (2000a) studied trunk repositioning errors in subjects with chronic low back pain and control subjects, both with eyes open and eyes closed. Measurements of trunk position in space using a 3Space Tracker revealed no significant differences in repositioning error between twenty subjects with chronic low back pain and twenty control subjects, nor where any significant differences in repositioning error found attributable to visual condition (i.e., eyes open or closed).

No data regarding the effects of vision on the repositioning ability of the head could be found, but interestingly when cervical ranges of movements are performed with eyes-open, the standard deviations of measurements are 2 to 3 times greater than those in the eyes-closed situation (Nansel and Szlazak, 1994).

By and large, of the three systems that influence the control of posture – somatosensory, vestibular and visual, it is the visual system that seems to be least well understood (Wade and Jones, 1997). Whether or not the vision will affect the repositioning ability of the head is one of the objectives of the present study.

2.9 Backrest inclination and posture

Work performed at VDUs may require sitting still for a considerable time and usually involves small frequent movements of the eyes, head, arms, and fingers only. Maintaining a fixed posture over long periods of time causes muscle fatigue, and if this practice is consistent, can eventually lead to muscle pain and injury (U.S. Department of Labor, 1997). Using seats with a tilting capability is advocated as a solution to this problem. A Japanese study (Udo et al, 1999) investigated the effect of a tilting seat on back, lower back and legs during seated work. It was found that a rocking chair, in contrast to a fixed seating condition, subjectively reduced back and lower back pain as a result of its tilting capability. However, it was also noted that the mean frequency of tilting events with an angle exceeding 2° was only 9.6 per hour (minimum 0; maximum 27.6) and the average maximum tilting angle was 3.1° (minimum 0°; maximum 7°). In other words, word-processing operation essentially constrained the subjects' trunk more rigidly than general deskwork, rendering the tilting capability of a chair apparently useless. Therefore, the use of chairs with tilting capability may not be the total solution to the posture problem even though such chairs have been highly recommended (U.S. Department of Labor, 1997). In general, the effects of backrest inclination on the neck, upper back and shoulders has not been studied in detail. Physiologically, the tilting of the trunk (accompanying the tilting of chair) alters the head on trunk relationship. Establishing whether or not this also results in a change in position sense of the head on trunk is one of the objectives of the present study.

METHODOLOGY

3.1 Study design

A balanced posture is a state of equilibrium with minimal amounts of stress and strain in muscles and joints (Enoka, 1994). Maintenance of a balanced posture helps to protect the delicate structures of the neck against progressive deformation or even injury (Enoka, 1994). The repositioning ability of the head on the trunk is a direct reflection of the postural awareness of the neck (Revel et al., 1991). Any factors which affect the repositioning ability of the head on the trunk will possibly increase the risk of deviation from a balanced posture, and may therefore increase the chance of injury or progressive deformation.

This study assessed the ability of normal subjects to reposition their head to a pre-defined memorised position relative to the trunk after performing a standard series of movements of the cervical spine, both before and after fatigue of the upper trapezius muscles at the back of the neck and shoulders. The head-on-trunk movement was monitored by a three dimensional video motion analysis system using reflective markers attached onto the surface of the skin at various anatomic locations over the trunk, neck and head, as detailed in section 3.3.1.

Subjects performed the repositioning task while seated with three different inclinations of the chair backrest (backward, upright and forward), and two different visual conditions (eyes open and closed) for both the fatigued and non-fatigued condition, giving a total of twelve different combinations of fatigue, inclination and visual conditions. As such, the aim of this study was to evaluate (a) the effect of upper trapezius muscle fatigue on the repositioning ability of normal subjects, (b) the effect of vision on the repositioning ability of the normal subjects, (c) the effect of inclined trunk position on the repositioning ability of the normal subjects, and (d) the combined effect of these factors on the repositioning ability of the normal subjects.

3.2 Subject inclusion and exclusion criteria

The subject group included in this study was intended to be representative of a typical local working population, and the inclusion criteria were therefore normal male and female subjects between the ages of 18 and 55. Any subject who had suffered from an episode of neck pain after trauma (such as whiplash) or who had a history of cervical injury was excluded from the study, as were any subjects with cervical pathologies such as radiculopathy, myelopathy, or vertebrobasilar artery insufficiency (VBI). A complete list of the exclusion criteria is given in appendix A, and subjects were checked against these criteria before being included in the study. Ethical approval was obtained prior to commencing the study and all subjects gave their written informed consent (appendix B) before taking part in the study. The purpose and procedures of the experiment were clearly explained to each subject verbally and on a standard instruction sheet provided (appendix C).

Twenty normal volunteers (13 male subjects and 7 female) were recruited with with an overall mean age of 27.7 (SD = 5.5). Anthropometric details are included in table 3.1.

Subject no	Sex	Age (years)	Body Weight (kg)	Body Height (cm)
1	M	29	76	180
2	M	25	88	175
3	M	23	59	170
4	M	41	64	158

5	M	27	72	175
6	M	31	76	180
7	F	24	46	157
8	F	29	48	153
9	M	35	65	163
10	M	22	55	163
11	F	22	43	159
12	F	22	46	162
13	M	34	71	173
14	M	25	65	173
15	M	27	55	160
16	M	24	65	173
17	M	23	75	174
18	F	33	68	170
19	F	22	46.5	157
20	F	35	50	163
Mean		27.7	61.7	166.9
SD		5.5	12.7	8.3

Table 3.1. Subject anthropometry

3.3 Experimental arrangement

Anthropometric data including the gender, age, height and weight of the subjects were recorded before the experiment, and the subject was positioned in the chair. A standardized seating configuration was used in accordance with guidelines included under the occupational health and safety ordinance (Chapter 509 - Cap 509b) issued by the Hong Kong government.

3.3.1 Marker placement

All subjects wore collarless T-shirts to reduce tactile hints from the garments which might be used as a guide for repositioning, and to allow the markers to be clearly viewed. The subjects were asked to clean their face and upper chest, and the skin was then swabbed with Skin-Prep (Smith & Nephew, Largo, FL, USA) for marker attachment. Reflective spherical markers 25mm in diameter (3M, USA) were firmly secured to the prepared skin surface using double sided adhesive tape. Three markers were attached to the subjects' head at the left tragus (P1), right tragus (P2), and the inferior margin of the left orbit (P3), as shown in figure 3.1.

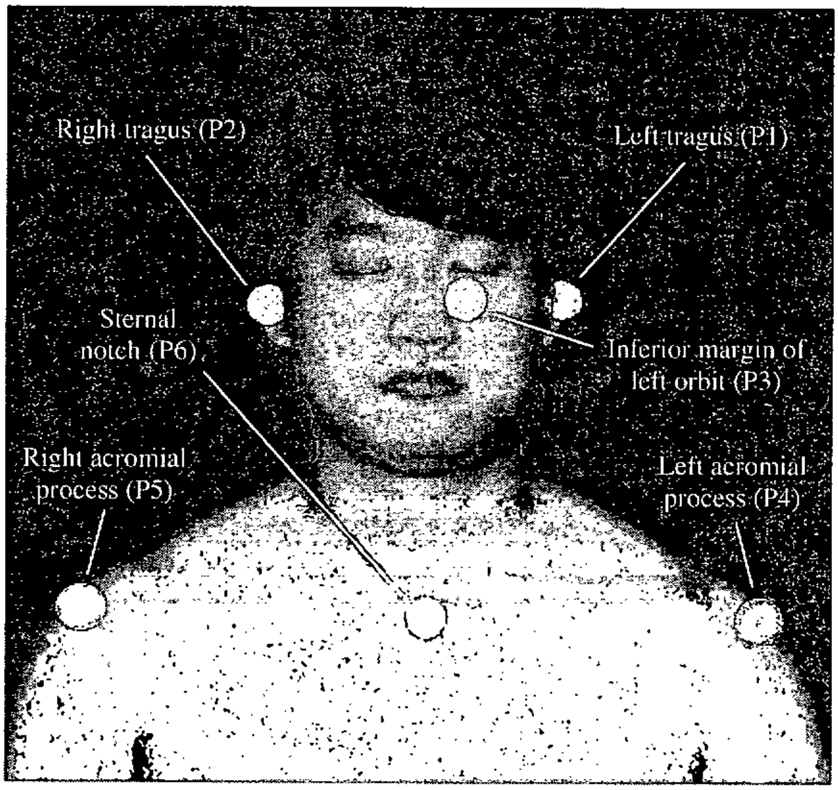


Figure 3.1. Placement of markers defining head and trunk.

Markers P1 and P2 at the left and right tragus are aligned to define the x-axis, and along with the marker P3 at the left inferior orbit form a horizontal plane parallel to the auriculonasal plane. The markers P1, P2 and P3 defined the position of the head, while another 3 markers (P4, P5 and P6) defined the position of the trunk (figure 3.1). The trunk markers were attached at the left acromial process (P4), the right acromial process (P5) and the sternal notch (P6).

3.3.2 EMG electrode placement

The electromyographic (EMG) activities of the bilateral upper trapezius muscles were monitored by a pair of surface electrodes attached along the direction of the muscle fibres to quantify muscle fatigue. The electrodes were placed at 38% of the distance from the edge of acromion to the spinuous process of the 7th cervical vertebra (Farina et al 2002). The location of each single differential recording system is defined as the mid-point between the two electrodes constituting the system. In order to minimize cross-talk and to ensure a good indication of muscle fatigue status, the inter-electrode distance was standardised at 20 mm (Farina et al., 2002). Prior to electrode fixation, the skin area was dry-shaved and rubbed with alcohol and ether (4:1). Skin impedance was checked with the purpose of achieving balance between the electrodes using the common mode test of the amplifier. Test muscle contractions were made before data collection to ensure that the EMG system (developed by the Jockey Club Rehabilitation Engineering Centre) was functioning properly with good electrode-skin contact and RMS noise levels less than 10μV.

3.3.3 Seating arrangement

Seating configurations were in line with the Hong Kong Government Labour Department recommendations included in "A health guide to working with display screen equipment" (http://www.info.gov.hk/labour/eng/public/index.htm). These state that the chair should:

- adjust easily from the seated position,
- have a slightly concave seatpan with a softly padded, rounded, or "waterfall" edge,
- have a seat that is approximately 18 inches wide (45.72 centimeters),
- have a back rest that provides lumbar support that can be used while working,

- have a stable base with casters that are suited to the type of flooring, have different seat pan lengths (15 to 17 inches or 38.10 and 43.18 centimeters) with a waterfall design available, and
- allow the seat pan to adjust for both height (minimum of 4 1/2 inches or 10.16-1.27 centimeters) and angle (plus or minus 5 degrees).

A standard office chair fulfilling the above requirements with an adjustable backrest tilt was used. The chair height was initially set to the "popliteal" height (the same height from the floor as the crease behind the subject's knee), and was then adjusted slightly such that the entire sole of the foot could rest on the floor or footrest and the back of the knee was slightly higher than the seat of the chair. This allows the blood to circulate freely in the legs and feet (U.S. Department of Labor, 1997). The elbow rests were adjusted to support both arms with the forearms parallel to the floor with elbows at the sides. The backrest allowed support of the entire back, including the lower region, and was adjusted to one of three positions (upright, forward tilt or backward tilt), according to the experimental protocol. The backrest inclination with respect to vertical axis was 14° to the front in the forward tilt position, 7° to the front in the upright position and 18° to the back in the backward tilt position.

3.3.4 Workstation configuration.

Table height, keyboard inclination and visual display unit (VDU) were adjusted in line with the Hong Kong Government Labour Department recommendations included in "A health guide to working with display screen equipment" (http://www.info.gov.hk/labour/eng/public/index.htm). Mouse pad, wrist rest and leg rest were also provided with adjustment accordingly.

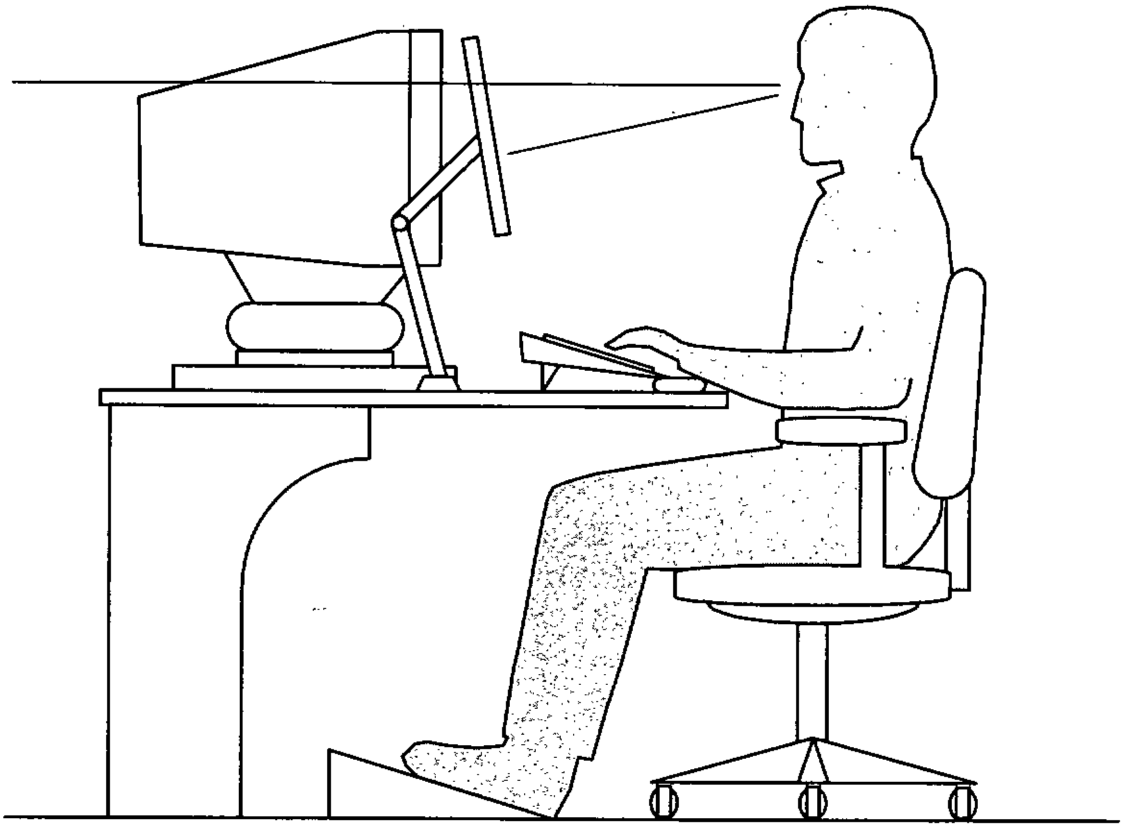


Figure 3.2. Seating and workstation configuration

3.4 Experimental protocol

The subject sat on the chair with the seat height, seat depth, armrest height, backrest height and footrest height adjusted in accordance with recommendations included in "A health guide to working with display screen equipment" (http://www.info.gov.hk/labour/eng/public/index.htm) (Hong Kong Government Labour Department, 2002). A three dimensional video motion analysis system (Vicon 370, Oxford Metrics Ltd., UK) was used to monitor the positions of the reflective markers attached to the trunk and head. Six cameras were used with data sampling rate of 120Hz. Camera #2 and camera #5 were installed at higher positions to increase the viewing angles subtended (Figure 3.3).

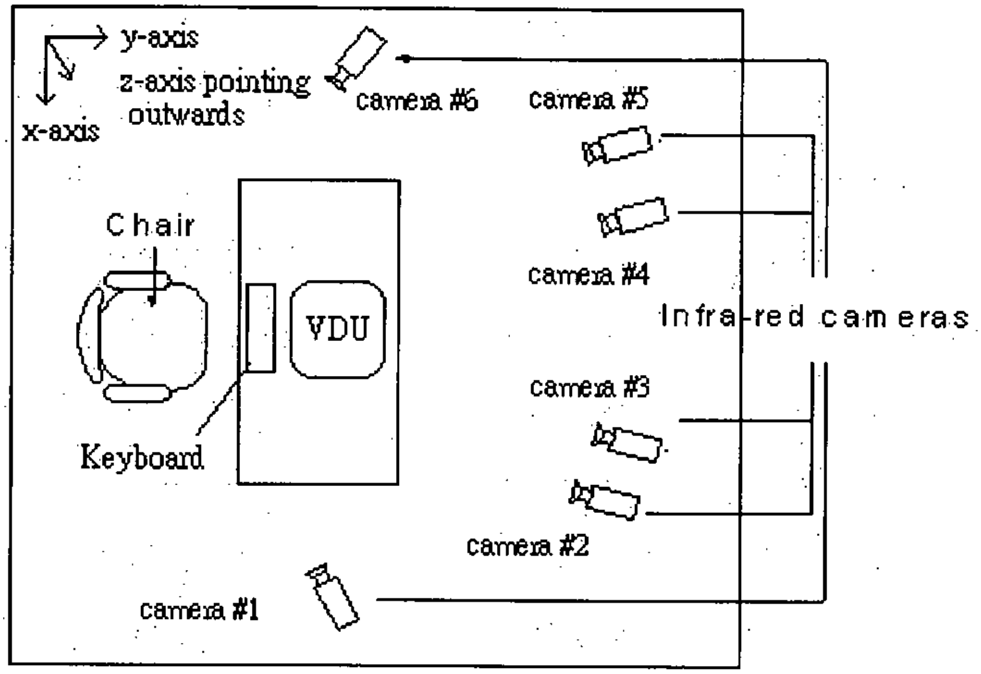


Figure 3.3. Floor plan of the laboratory and camera arrangement

The motion analysis system was calibrated following the manufacturers guidelines before each experimental session. The origin of the global Cartesian coordinate system of the motion analysis system was defined with x-axis aligned with medio-lateral direction parallel to the edge of table, the y-axis aligned with the postero-anterior direction towards VDU and the z-axis aligned with the vertical direction.

The subject was initially asked to adopt a normal comfortable working posture with backrest inclination (i.e. upright, forward or backwards) and the visual status (eyes open or closed) adjusted according to the randomized order of seating and visual configurations. Subjects were asked to focus or imagine focussing on the VDU at all times in the eyes open situation, or imagine focusing on the VDU in the eyes closed situation. Subjects were also asked to rest their elbows onto the armrest with wrist on support and hands on keyboard but no movement during motion capture to simulate the real working scenario. The starting posture was recorded for 2 seconds using the motion analysis system. Subjects were asked to memorize this posture, and then instructed to perform maximal cervical flexion, extension, right rotation, left rotation, right side flexion and left side flexion in that order before returning the head to the memorized posture, which was again captured for a duration of 2 seconds. This process of sequential motion and reproduction of the memorized position was repeated 10 times, such that 10 repeats of the memorized position were recorded for that condition of chair back inclination, vision, and fatigue. After the 10 repeats, chair back inclination (upright, forward or backwards) and the visual status (eyes open or closed) were altered in a randomized order and 10 repeats of the memorized position were recorded for each chair back inclination and visual status in the unfatigued condition. This amounted to a total of 60 (10 x 3 x 2) repeats of the cervical motion and repositioning procedure. Approximately one minute rest was given between different configurations, and the entire process took roughly an hour to complete.

Following collection of the non-fatiguing data, the subject performed an isometric shoulder exercise as detailed in section 3.4.1 to induce fatigue of the upper trapezius muscles. Immediately after this the subject performed the repositioning ability test again for ten repeats at each of the chairback positions and visual conditions, again in randomized order.

After the repositioning ability tests had been completed, the maximal ranges of motion of the cervical spine in the sagittal, coronal and transverse planes as well as the maximum protraction and retraction were the measured at the maximum positions for 2 seconds. Maximum ranges were calculated with reference to the anatomical neutral position, in which the subject was passively placed in a position with zero cervical flexion or extension, side flexion (side bending), rotation and protraction / retraction by the plumbline method (Kendall et al., 1983).

3.4.1 Fatigue procedure

The metabolic and physiological changes during fatigue resulting from long-duration and short-duration fatiguing exercises are distinct (Chaffin and Andersson, 1991), and a long duration sub-maximal fatiguing exercise was chosen because the fatigue pattern is likely to be similar to that due to the daily activities of sedentary workers. Subjects were asked to flex both shoulders to 90 degrees with horizontal flexion of 30 degrees and full elbow extension with pronated hands, and maintain this position for as long as possible to a maximum of 30 minutes. This shoulder flexion task was repeated before each of the 6 different seating and visual configurations investigated, and is associated with a glenohumeral torque of between 7.4 and 10.3 Nm according the following formula (Chaffin and Andersson 1991):

$$\text{Torque} = 9.81 \times 0.048 \times m \times 0.50 \times d$$

(where m is the body mass and d is the shoulder-wrist distance).

Biomechanically, this torque corresponds to 15-20% of the subject's MVC, according to the literature on maximal glenohumeral strength (Mathiassen and Aminoff, 1997). EMG activity was recorded to identify the fatigue condition of the upper trapezius muscles, and an eleven–grade (0-10) category scale with ratio properties was also used for rating the subjective perception of muscular fatigue of the upper trapezius muscles throughout the test (Oberg, 1994). All subjects rated their own perceived muscular fatigue level every minute during the fatigue test.

3.5 Data collection

Surface EMG activity was recorded using a bipolar multi-channel EMG amplifier (common-mode rejection ratio higher than 100dB, input noise <1 μV). The signals were detected in single differential mode to minimize line interference. All signals were amplified and digitized at 12 bit accuracy in the signal range ± 5 V with a sampling rate of 2 kHz. Analogue low-pass filters of 800Hz were used to eliminate aliasing of the sampled EMG signals. The power-density spectrum was obtained using the fast Fourier transform (FFT) technique after Hamming windowing. To yield a spectral resolution of 2 Hz, a 1024-point FFT (512ms) was selected. The mean power frequency (MPF) was calculated from all the signals detected in epochs of 1s, without overlapping. All obtained EMG variables were averaged after discarding any epochs showing artifacts. The shift of electromyogram (EMG) frequency spectrum towards lower frequencies was used as an estimator of muscle fatigue (Oberg et al., 1990). The relative decrease in Mean Power Frequency (MPF) is significant if it exceed 8% of the initial MPF (MPF_0) as a result of muscle fatigue (Oberg et al., 1990).

Mean Power Frequency (MPF) was estimated over the fatiguing contractions period and results indicated fatigue of the upper trapezius muscles.

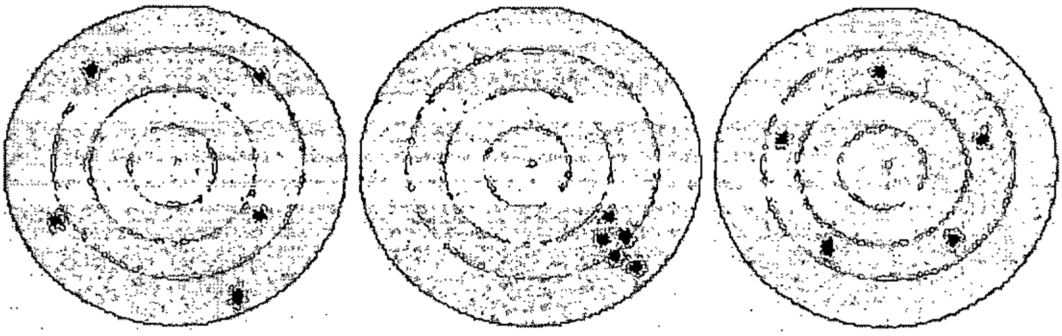
3.5.1 Repositioning ability measures

The marker positions were recorded for 2 seconds at the memorized position and stored on a workstation PC. A purpose-written computer program (appendix E) was then used to determine the angular and translational deviations between the initial memorized criterion position and the consequent reproductions of this memorized position. According to error theory (Chow, 2001) the repositioning ability can be interpreted in three different ways using different measures. The three measures used were the mean error (ME), the absolute error (AE) and the variability error (VE).

The mean error is simply the mean of the deviations of the 10 reproductions of the memorized position from the initial memorized criterion position. This is calculated for each configuration of visual status and chairback inclination, and represents the subject's mean accuracy in reproducing the memorized position. A negative mean error would indicate that the mean reproduced position was less than that of the memorized position, while a mean error of zero would imply that the subject managed, on average, to reproduce the memorized position exactly. However, a mean error of zero does not necessarily mean that the subject managed to reproduce the memorized position exactly at each attempt, since a large overshoot combined with a large undershoot will tend to give a mean error of zero. For this reason, the absolute error (AE) was also calculated, which is simply the mean of the absolute value of the difference between the 10 reproduced positions and the initial memorized criterion position. This therefore represents the mean angular or translational distance of the reproduced positions from the memorized position.

While both the mean error (ME) and absolute error (AE) indicate the subject's accuracy in reproducing the memorized position, neither of these values give any indication of the consistency of the reproduced position (i.e. repositioning precision). Therefore the variability error (VE) was also calculated as the standard deviation of the 10 mean error values for a particular visual status and chairback inclination. A large positive ME and a low VE would therefore mean that the reproduced position was consistently greater than the memorized position for all 10 reproductions of this position.

This is illustrated in figure 3.4, which shows how the reproduced position can be precise but inaccurate (figure 3.4b), or accurate but imprecise (figure 3.4c).



(a) large ME,
largeVE

(b) large ME,
lowVE

(c) low ME,
largeVE

Figure 3.4. Illustration of repositioning accuracy in terms of the mean error (ME) and repositioning precision in terms of the variability error (VE)

As illustrated in figure 3.4c, the mean accuracy (ME) can be low, even if all of the reproduced positions deviate substantially from the memorized position. To eliminate the pitfall of overlooking situations where the ME appears low due to the sum of positive and negative errors tending towards zero, the absolute error (AE) was also evaluated. The AE was defined as the absolute value of the deviation between the subject's responses and the initial memorized position, and therefore gives an indication of both the accuracy and precision (bias and variability) of the repositioning. The absolute errors of all the ten trials for each condition were also averaged. The relationship between ME, VE and AE is illustrated in one dimension in figure 3.5. The memorized position is shown as a line, and the individual repositioning points as dots. The mean position of the dots (the mean error) is shown as a dashed line. So the mean error shown in figure 3.5(a) is almost zero. In figure 5.2(b) the spread of dots is the same, so the standard deviation (VE) is the same as in 3.5(a), but the points are all lower than the memorized position, i.e., ME is larger than in 3.5(a), but negative. The value of AE in 3.5(b) is also larger than that in 3.5(a), as the average deviation of each dot from the black line (memorized position) has

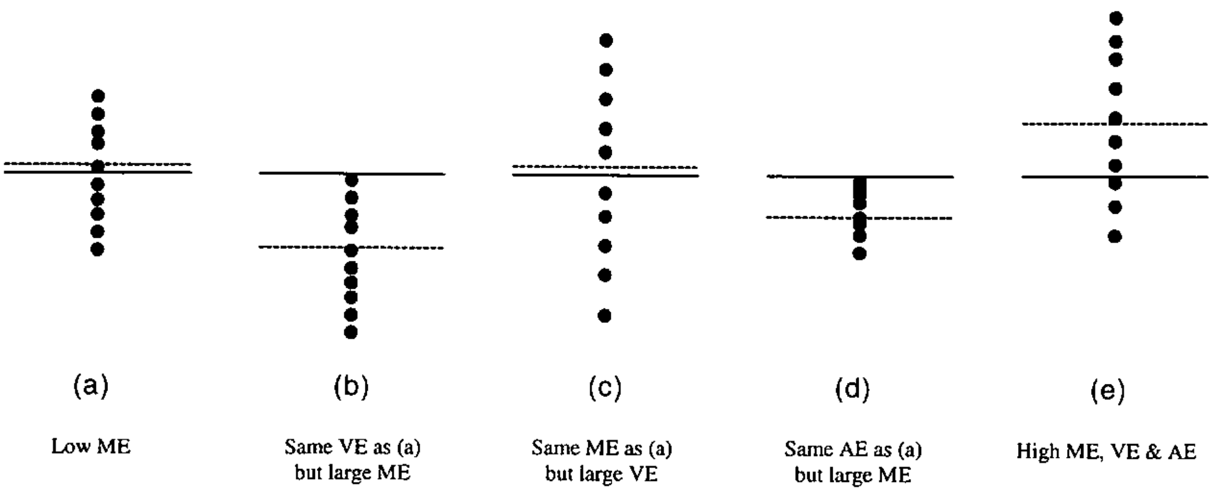


Figure 3.5. Relationship between repositioning accuracy (ME), precision (VE), and absolute error (AE). The memorized position is represented as the solid black line, and each of the reproduced positions as dots. The ME is therefore represented by the mean position of the dots (the broken line), the VE by the spread of the dots, and the AE by the absolute distance of the dots from the solid line.

increased. In 3.5(c), the ME is the same as in 3.5(a), except now that the points are more widely spread, so the standard deviation (VE) is higher, and the average deviation of a dot from the black line (AE) is again higher. So while the accuracy (ME) and precision (VE) are independent, both have an effect on AE.

Figure 3.5(d) shows the case where all the dots that were above the black line in 3.5(a) are now the same distance below it. This means that the mean deviation from the dots to the line is the same as in 3.5(a), i.e., the AE is the same. However, although the dots are on average no further away from the memorized position than in 3.5(a), they all undershoot the memorized position, and ME is therefore larger than in 3.5(a), but negative. As the dots are closer together, then the VE in case 3.5(d) is lower than that of 3.5(a). In 3.5(e), the dots are more widely spread than in 3.5(a), so VE is increased, and this also increases the mean deviation (AE) from the memorized position. The ME in 3.5(e) is also greater than in 3.5(a), which further increases the

AE. So the AE in 3.5(e) is greater than that in 3.5(a) partly due to the increase in VE and partly due to the increase in ME.

3.5.2 Reference coordinate systems

Di Frabio and Emasithi (1997) outlined three reference systems in postural control, namely the egocentric, exocentric and geocentric reference systems. The egocentric reference system concerns the relative spatial orientation of body segment systems, such as the head on trunk relationship, where the trunk position is used as the reference. The exocentric reference system refers to the body position with respect to the external environment, such as the Video Display Unit (VDU), while the geocentric system refers to the position of the body with respect to the gravitational field. Body positions have 6 degrees of freedom in each of these reference systems, consisting of translation and rotation about the x, y, z-axis of an orthogonal coordinate system.

In this study, there is no motion of the exocentric system with respect to the geocentric system, and therefore these two systems were lumped together as the global system, and the specific egocentric system of the head motion with respect to the trunk was defined as the local system. The local system therefore allows the repositioning error to be defined simply in physiological terms as follows:

Local System	Positive "+"	Negative "-"
X-axis rotation	Flexion	Extension
Y-axis rotation	Right lateral flexion	Left lateral flexion
Z-axis rotation	Left axial rotation	Right axial rotation
X-axis translation	Right sidegliding	Left sidegliding

Y-axis translation	Head protraction	Head retraction
Z-axis translation	Axial distraction	Axial compression

The global reference frame was defined with respect to the gravitational field and the workstation. The z-axis was aligned with the gravitational field, and the y-axis defined as the horizontal line from the subjects' head to the video display unit (VDU) of the workstation. The x-axis (left – right axis) was defined as the cross product of the x and z axes, with sign convention given below:

Global System	Positive "+"	Negative "-"
X-axis rotation	Towards bottom of VDU	Towards top of VDU
Y-axis rotation	Towards right lower corner of VDU	Towards left lower corner of VDU
Z-axis rotation	Towards left of VDU	Towards right of VDU
X-axis translation	Towards right of VDU	Towards left of VDU
Y-axis translation	Towards VDU	Away from VDU
Z-axis translation	Up	Down

3.6 Data analysis

Statistical analysis of the experimental data were carried out by three way repeated measures analysis of variance (ANOVA), using the general linear model included in the SPSS 11.5 statistical software package (SPSS Inc., Chicago, Ill. USA), and level of significance set at p=0.05 throughout. The within subjects factors of the three way repeated measures ANOVA were the fatigue condition (before or after fatiguing protocol), the visual status (eyes open or closed) and the inclination of the chair back (forward, upright or backward). If any interaction was found between parameters, then repeated measures ANOVA was conducted for interacting factors separately. In such cases the level of significance was adjusted according to Bonferroni criteria to maintain the family-wise type I error rate at a level equal to $p=0.05$ (Keppel, 1991). Post-hoc comparisons of significant effects were made using Bonferroni criteria.

RESULTS

The mean error (ME), absolute error (AE) and variability error (VE) indicating the subject's ability in reproducing the memorized position were analyzed separately using 3-way Repeated Measure ANOVA with visual status, chairback inclination and fatigue status as within-subjects factors. The reproduction of the memorized position was further defined by the translational and angular parameters with respect to the local and global reference systems. The arrangement of overall data analysis was summarized in table 4.1.

	Angular		Translational	
	Global	Local	Global	Local
Mean Error (ME)	Result in Section 4.1.1	Result in Section 4.1.2	Result in Section 4.1.3	Result in Section 4.1.4
Absolute error (AE)	Result in Section 4.2.1	Result in Section 4.2.2	Result in Section 4.2.3	Result in Section 4.2.4
Variability error (VE)	Result in Section 4.3.1	Result in Section 4.3.2	Result in Section 4.3.3	Result in Section 4.3.4

Table 4.1. Table summarizing the overall arrangement of data analysis and reporting

All three of the within-subject factors (fatigue condition, visual status, and chairback inclination) were found to have significant effects on the subjects' ability to reproduce the memorized position, as detailed in the following sections.

4.1 Repositioning mean error (ME)

4.1.1 Angular repositioning ME in the global reference system

No significant effects of visual status, chairback tilt or fatigue were found for any of the angular rotations in the global system, nor were any significant interactions found between these factors (table 4.2, figure 4.1., figure 4.2. & figure 4.3.) , with the exception of rotation around the x-axis, which showed a significant (p=0.020) interaction between fatigue, tilting and vision. As such, repeated measures ANOVA was conducted for each condition of fatigue, tilting and vision separately. The results are summarized in figure 4.4.,

Source of main effect / interaction	x-axis rotation	y-axis rotation	z-axis rotation
Fatigue	p=0.346	p=0.434	p=0.843
Tilting	p=0.360	p=0.502	p=0.698
Vision	p=0.397	p=0.880	p=0.378
Fatigue * tilting	p=0.916	p=0.223	p=0.376
Fatigue * vision	p=0.214	p=0.206	p=0.426
Tilting * vision	p=0.093	p=0.858	p=0.335
Fatigue * tilting * vision	p=0.020*	p=0.300	p=0.056

Table 4.2. Significances of main effects and interactions for the mean angular repositioning error (ME) in the global reference system. P-values are marked with an asterisk where significant.

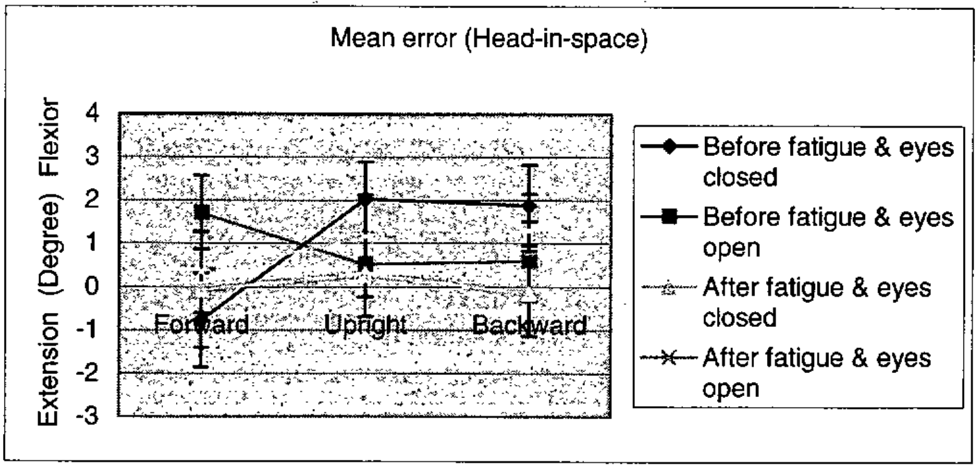


Figure 4.1. Mean angular repositioning error (ME) around the x-axis in the global system for each chairback inclination under different fatigue and visual conditions.

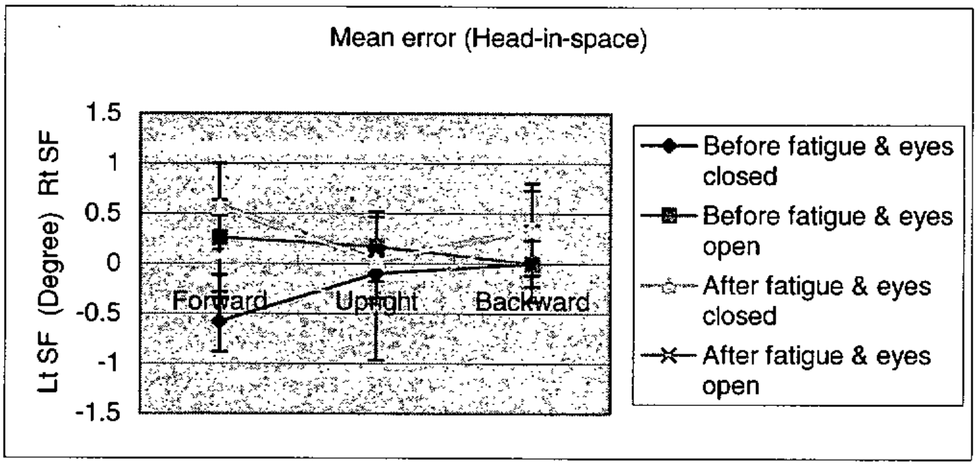


Figure 4.2. Mean angular repositioning error (ME) around the y-axis in the global system for each chairback inclination under different fatigue and visual conditions.

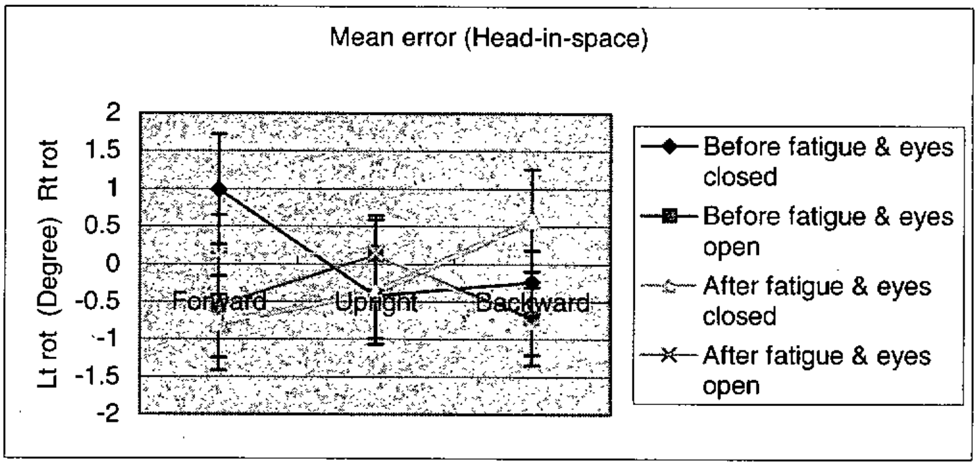


Figure 4.3. Mean angular repositioning error (ME) around the z-axis in the global system for each chairback inclination under different fatigue and visual conditions.

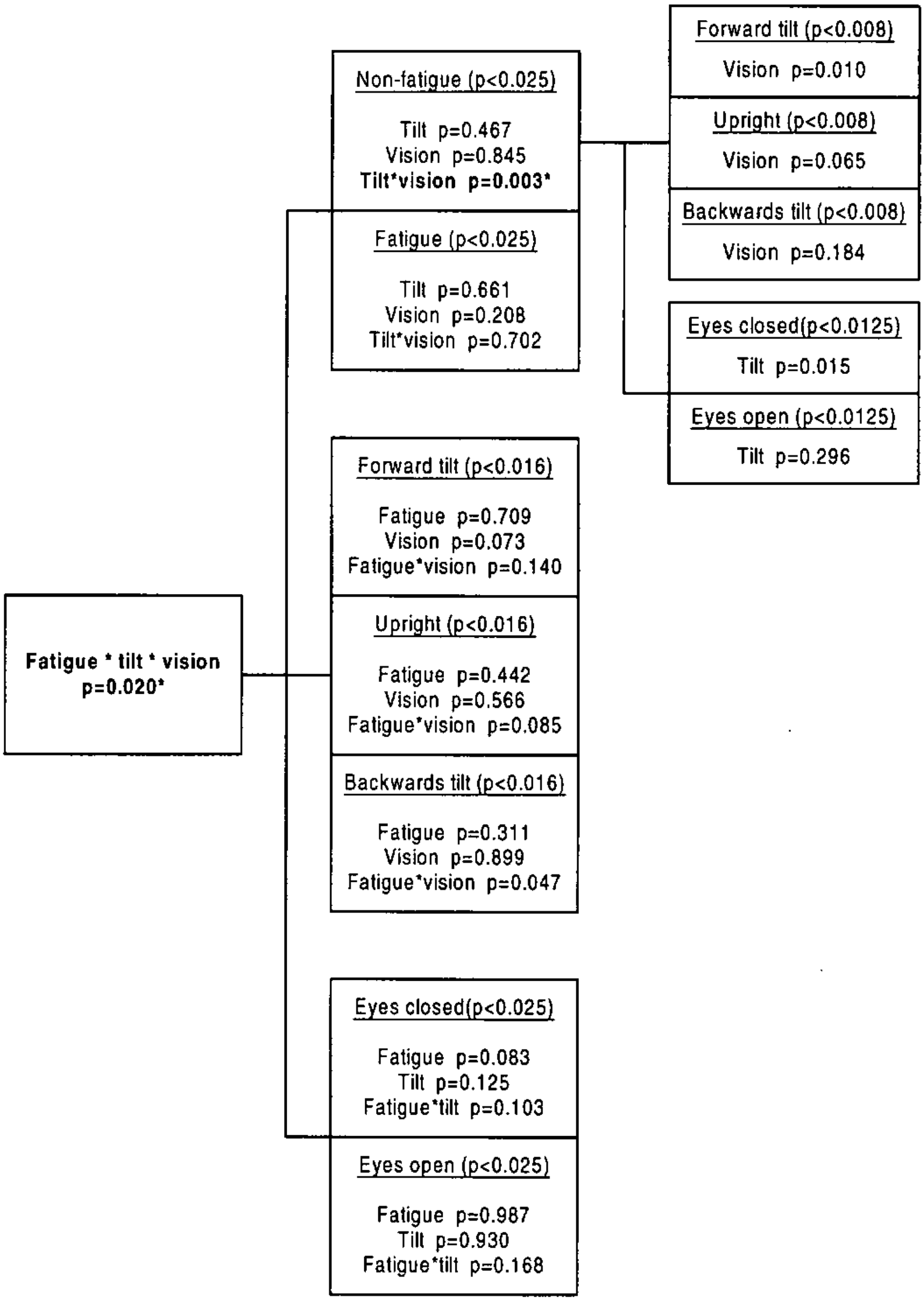


Figure 4.4. Separate repeated measures ANOVA for mean angular repositioning error (ME) around the x-axis in the global system. Bonferroni adjusted significance levels are indicated in brackets for each condition, and significant effects are marked in bold with an asterisk.

No significant main effects of fatigue or tilt were found with either the eyes open or closed, nor were any significant effects of fatigue or vision found at any of the chairback inclinations. The only significant result was found in the non-fatigued situation, where there was a significant interaction between tilt and vision. However, no significant effect of vision was found at any of the chairback inclinations before fatigue, and similarly no significant effects of tilt were either with the eyes open or eyes closed.

Source of main effect / interaction	Flexion	Lateral flexion	Axial rotation
Fatigue	p=0.306	p=0.379	p=0.801
Tilting	p=0.345	p=0.412	p=0.722
Vision	p=0.384	p=0.528	p=0.688
Fatigue * tilting	p=0.900	p=0.287	p=0.844
Fatigue * vision	p=0.212	p=0.192	p=0.452
Tilting * vision	p=0.081	p=0.781	p=0.473
Fatigue * tilting * vision	p=0.018*	p=0.214	p=0.247

Table 4.3. Significances of main effects and interactions for the mean angular repositioning error (ME) in the local reference system. P-values are marked with an asterisk where significant.

4.1.2 Angular repositioning ME in the local reference system

The mean angular repositioning error was also calculated with reference to the local system, i.e., the repositioning error of the head on the trunk, as opposed to the external environment. Results of the 3-way repeated measures ANOVA are shown in table 4.3, figure 4.5., figure 4.6. & figure 4.7., and while no significant main effects

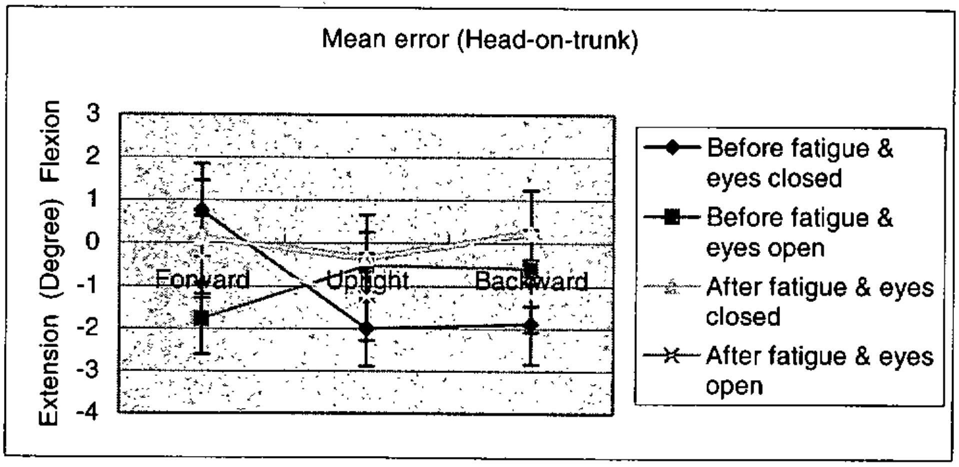


Figure 4.5. Mean angular repositioning error (ME) around the x-axis in the local system for each chairback inclination under different fatigue and visual conditions.

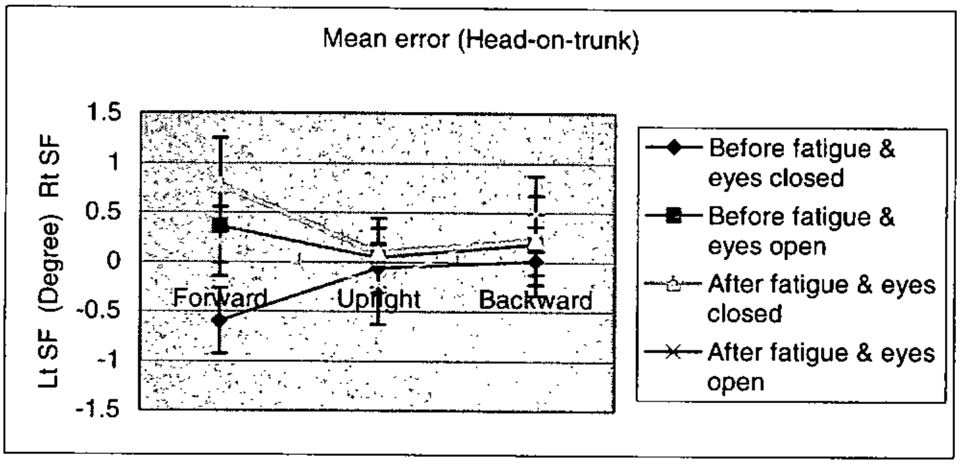


Figure 4.6. Mean angular repositioning error (ME) around the y-axis in the local system for each chairback inclination under different fatigue and visual conditions.

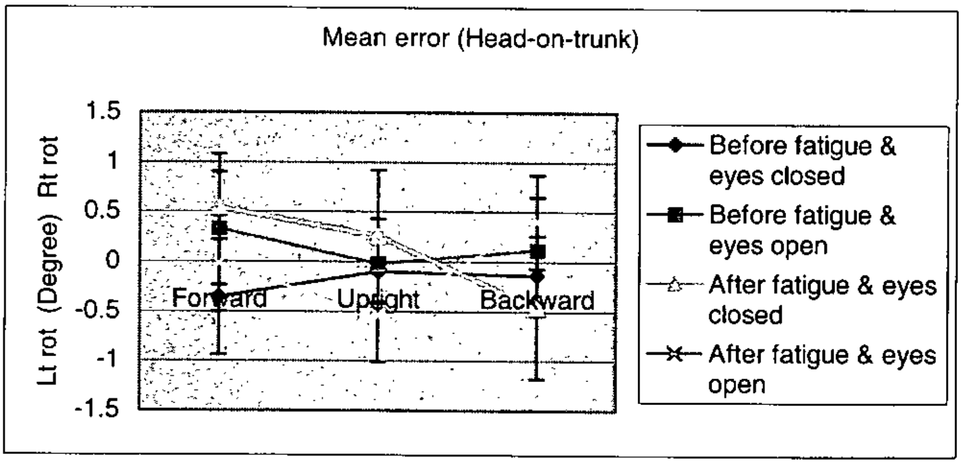


Figure 4.7. Mean angular repositioning error (ME) around the z-axis in the local system for each chairback inclination under different fatigue and visual conditions.

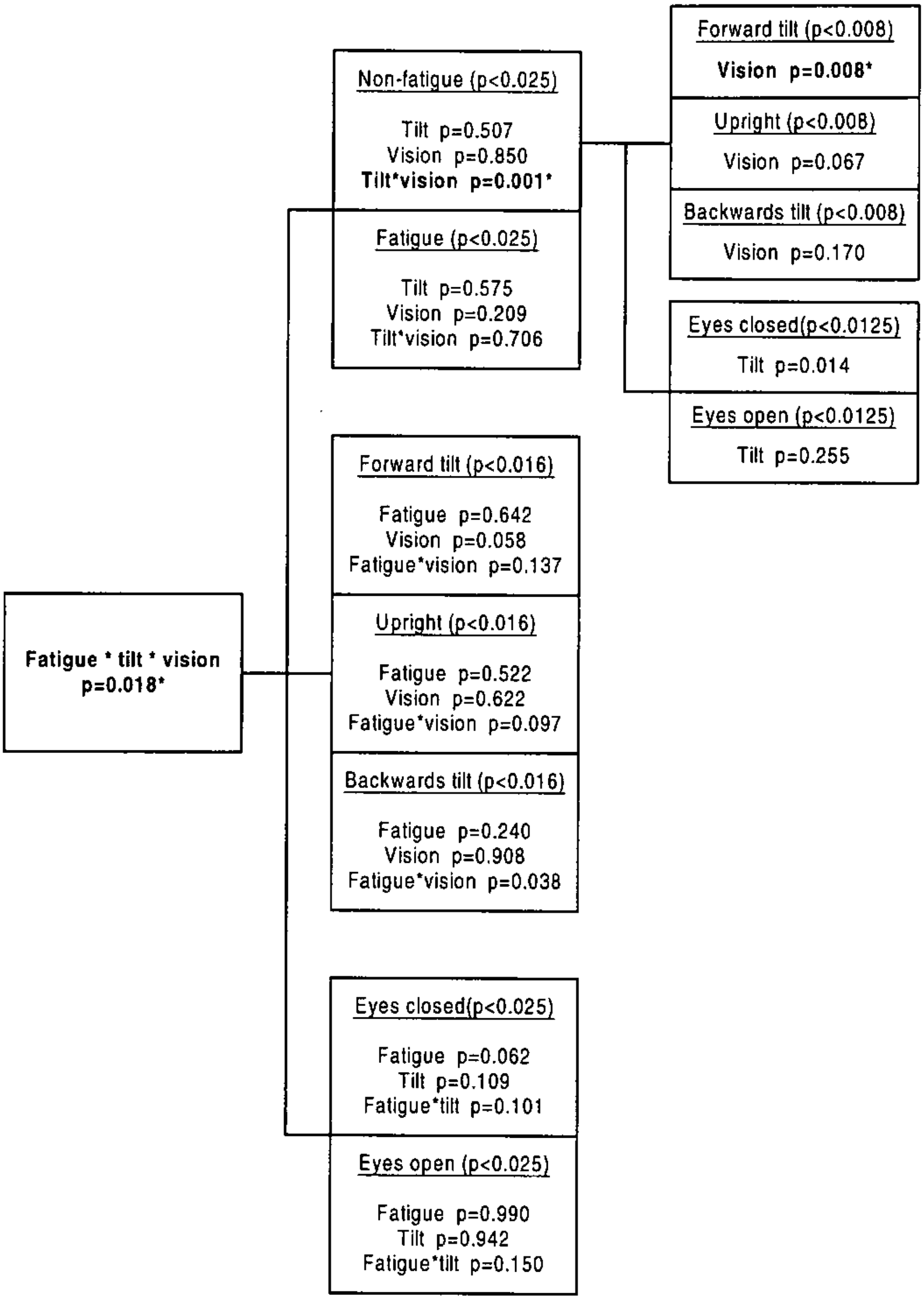


Figure 4.8. Separate repeated measures ANOVA for mean flexion angle repositioning error (ME) in the local system. Bonferroni adjusted significance levels are indicated in brackets for each condition, and significant effects are marked in bold with an asterisk.

were found, a significant interaction between fatigue, tilt and vision was found, similar to the results in the global system. Repeated measures ANOVA were performed for different fatigue, tilt and vision conditions separately (figure 4.8), and results were again similar to those found in the global reference system, where the only significant result proved to be an interaction between tilt and vision for the unfatigued condition (p=0.018). However, in this case, further analysis showed a significant effect of vision for the seat forward configuration, with the mean error with eyes closed (0.8°) being significantly higher than that with eyes open (-1.8°).

4.1.3 Translational repositioning ME in the global reference system

While fatigue, tilt and vision had no effect on the angular mean error in the global system, translations in the global reference system showed significant main effects of fatigue and tilting (table 4.4, figure 4.9., figure 4.10. & figure 4.11.). The mean translational error in the x-axis was found to be significantly greater after fatigue, with a mean value of 0.8mm as compared to a mean value of –0.4mm before fatigue. The mean translational error in the z-axis was also found to be significantly affected by the seat tilt, with a mean error of 1.4mm at the forward position, 0.5mm at the upright position, and 0.2mm at the backwards inclination. Post-hoc multiple comparisons using Bonferroni criteria showed the mean error at the forward position to be greater than that at the upright and backwards positions (p=0.043 and p=0.045 respectively).

Significant main effects of tilting was found for the mean y-axis translational repositioning error in the global reference system, but a significant interaction between fatigue, tilting and vision was also found in this case (table 4.4, figure 4.9, figure 4.10 & figure 4.11), and the results were therefore separated by factor for further analysis (figure 4.12).

Source of main effect / interaction	x-axis translation	y-axis translation	z-axis translation
Fatigue	p=0.049*	p=0.401	p=0.121
Tilting	p=0.668	P=0.001*	p=0.010*
Vision	p=0.978	p=0.065	p=0.839
Fatigue * tilting	p=0.137	p=0.598	p=0.196
Fatigue * vision	p=0.416	p=0.488	p=0.076
Tilting * vision	p=0.716	p=0.695	p=0.086
Fatigue * tilting * vision	p=0.336	p=0.036*	p=0.068

Table 4.4. Significances of main effects and interactions for the mean translational error (ME) in the global reference system. P-values are marked with an asterisk where significant.

A significant effect of chairback tilt was found in the non-fatigued condition, and post-hoc comparisons using Bonferroni criteria showed the mean error with backwards tilt (2.0mm) to be significantly greater than that with upright chairback (p=0.041, mean error –1.7mm) and that with forwards tilt (p=0.007, mean error – 3.7mm).

Significant effects of chairback tilt were also found in both the eyes open and eyes closed conditions (figure 4.12). With eyes closed, post-hoc multiple comparisons showed the mean error in the forward position (-4.9mm) to be significantly lower than that in the backwards position (0.3mm, p=0.037). A similar effect was seen with eyes open, where the mean error in the backwards position (1.5mm) was significantly higher than that in the upright position (-1.6mm, p=0.028) and that in the forward position (-2.8mm, p=0.001).

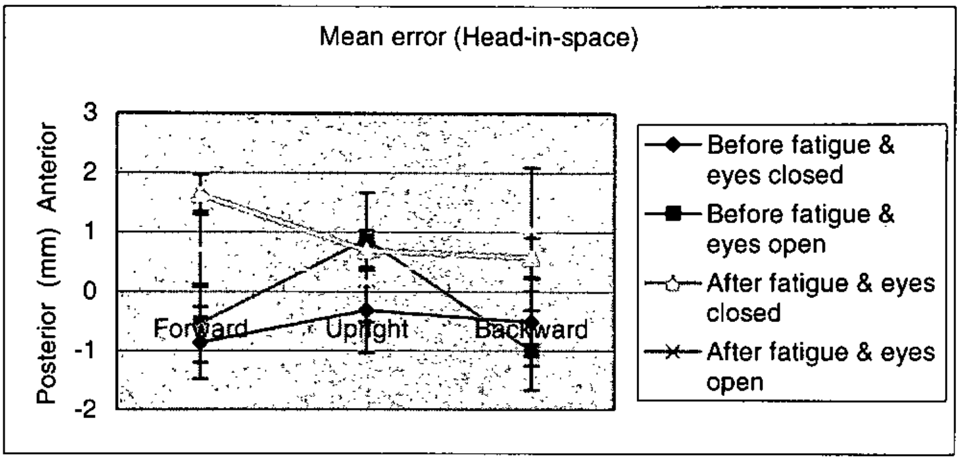


Figure 4.9. Mean translational repositioning error (ME) around the x-axis in the global system for each chairback inclination under different fatigue and visual conditions.

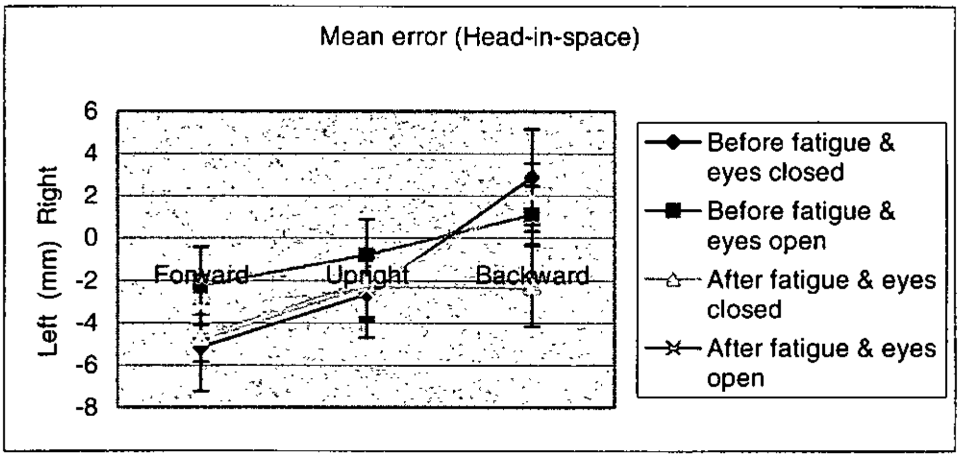


Figure 4.10. Mean translational repositioning error (ME) around the y-axis in the global system for each chairback inclination under different fatigue and visual conditions.

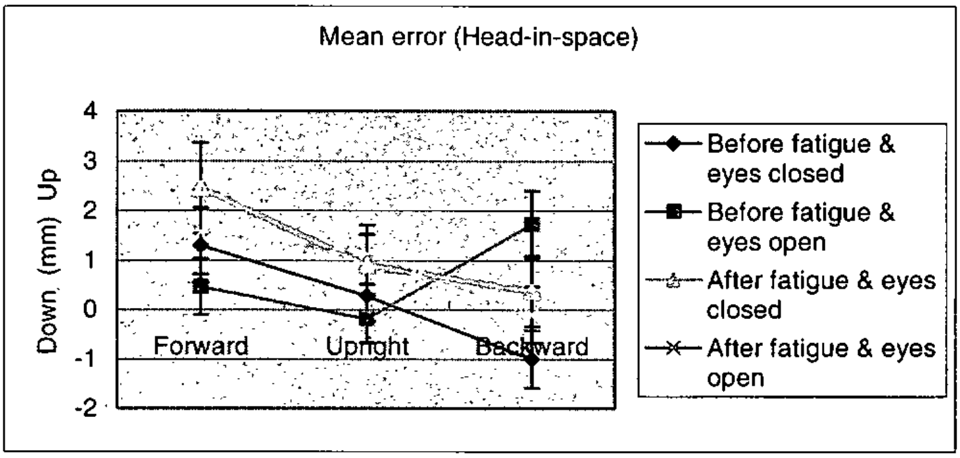


Figure 4.11. Mean translational repositioning error (ME) around the z-axis in the global system for each chairback inclination under different fatigue and visual conditions.

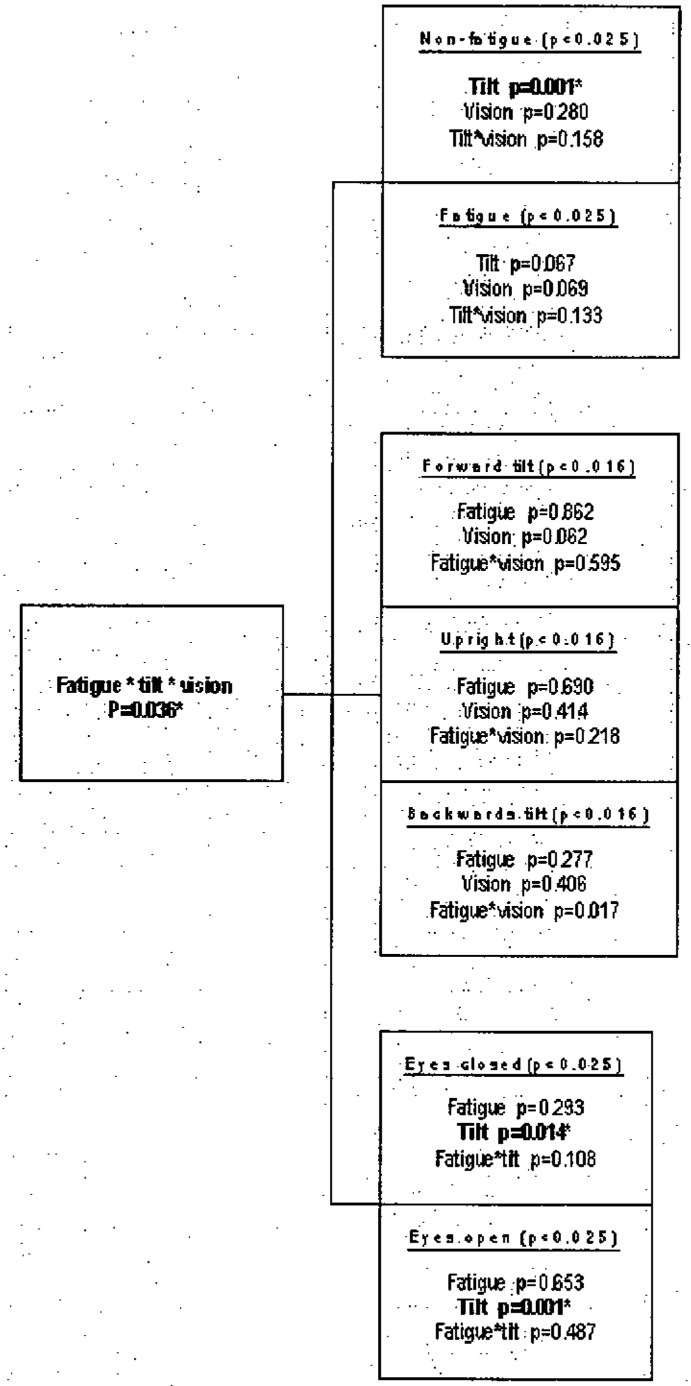


Figure 4.12. Separate repeated measures ANOVA for mean translational repositioning error (ME) along the y-axis of the global system. Bonferroni adjusted significance levels are indicated in brackets for each condition, and significant effects are marked in bold with an asterisk.

4.1.4 Translational repositioning ME in the local reference system

When mean translation errors were considered in the local reference system (head on trunk motion), a significant main effect of fatigue was found for head sidegliding. The mean translational error was found to be significantly greater after fatigue, with a mean value of 0.9mm as compared to a mean value of –0.3mm before fatigue. Significant interaction between fatigue and vision was also found for head protraction, and significant interactions between fatigue and tilting as well as fatigue and vision for head distraction (table 4.5, figures 4.13, 4.14 and 4.15). Further repeated measures ANOVA was therefore done for separate factors (figures 4.16, 4.17 and 4.18).

Further repeated measures ANOVA for head protraction (figure 4.16) showed a significant interaction between fatigue and tilting when the eyes were closed. Consequent Post-hoc multiple comparisons showed that the mean error before fatigue (-4.1mm, p=0.003) to be significantly lower than that after fatigue (2.3mm) for the eyes closed, seat tilted back condition (figure 4.16).

Source of main effect / interaction	Sidegliding	Protraction	Axial distraction
Fatigue	p=0.019*	p=0.611	p=0.724
Tilting	p=0.963	P=0.113	p=0.630
Vision	p=0.860	p=0.961	p=0.243
Fatigue * tilting	p=0.089	p=0.122	p=0.044*
Fatigue * vision	p=0.148	p=0.036*	p=0.025*
Tilting * vision	p=0.472	p=0.772	p=0.135
Fatigue * tilting * vision	p=0.383	p=0.059	p=0.564

Table 4.5. Significances of main effects and interactions for the mean translational error (ME) in the local reference system. P-values are marked with an asterisk where significant.

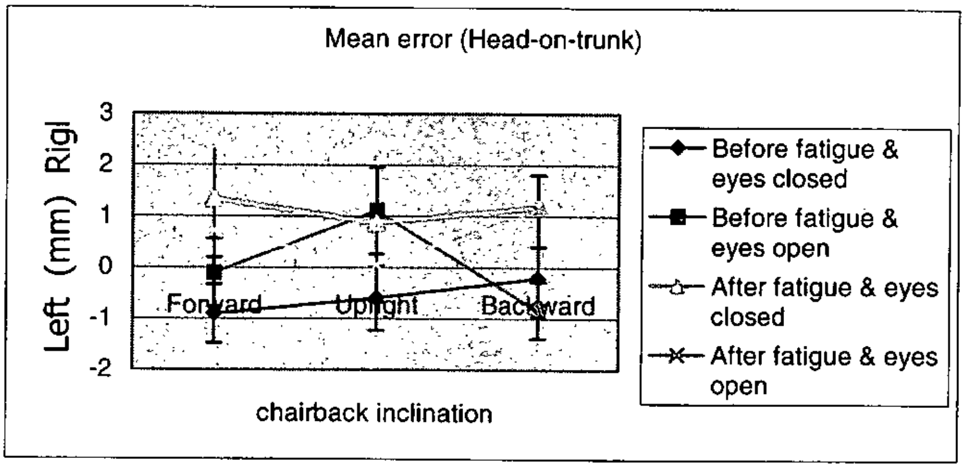


Figure 4.13. Mean translational repositioning error (ME) around the x-axis in the local system for each chairback inclination under different fatigue and visual conditions.

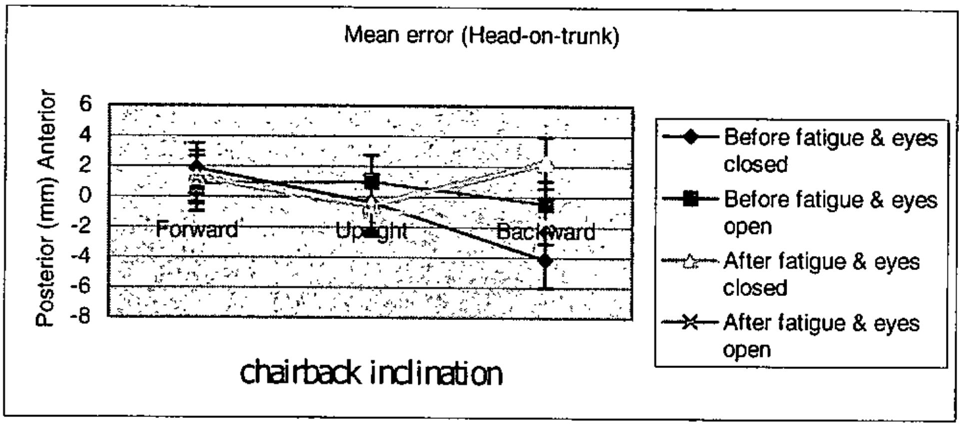


Figure 4.14. Mean translational repositioning error (ME) around the y-axis in the local system for each chairback inclination under different fatigue and visual conditions.

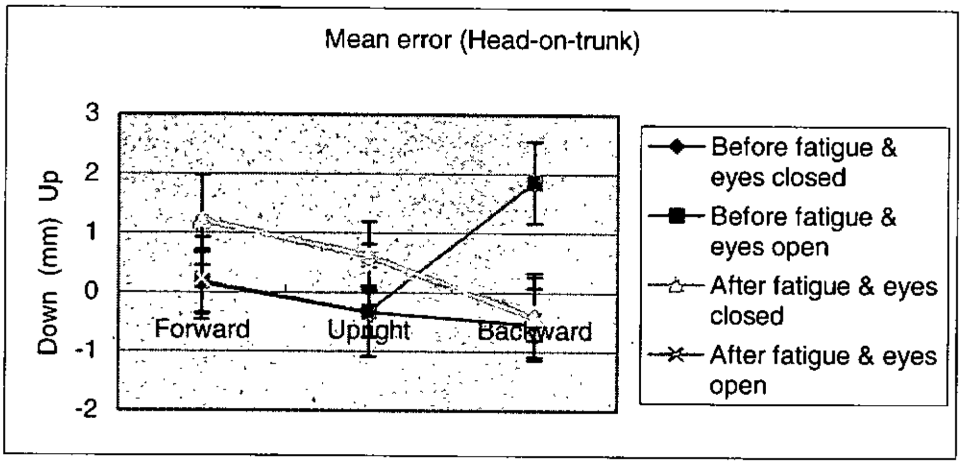


Figure 4.15. Mean translational repositioning error (ME) around the z-axis in the local system for each chairback inclination under different fatigue and visual conditions.

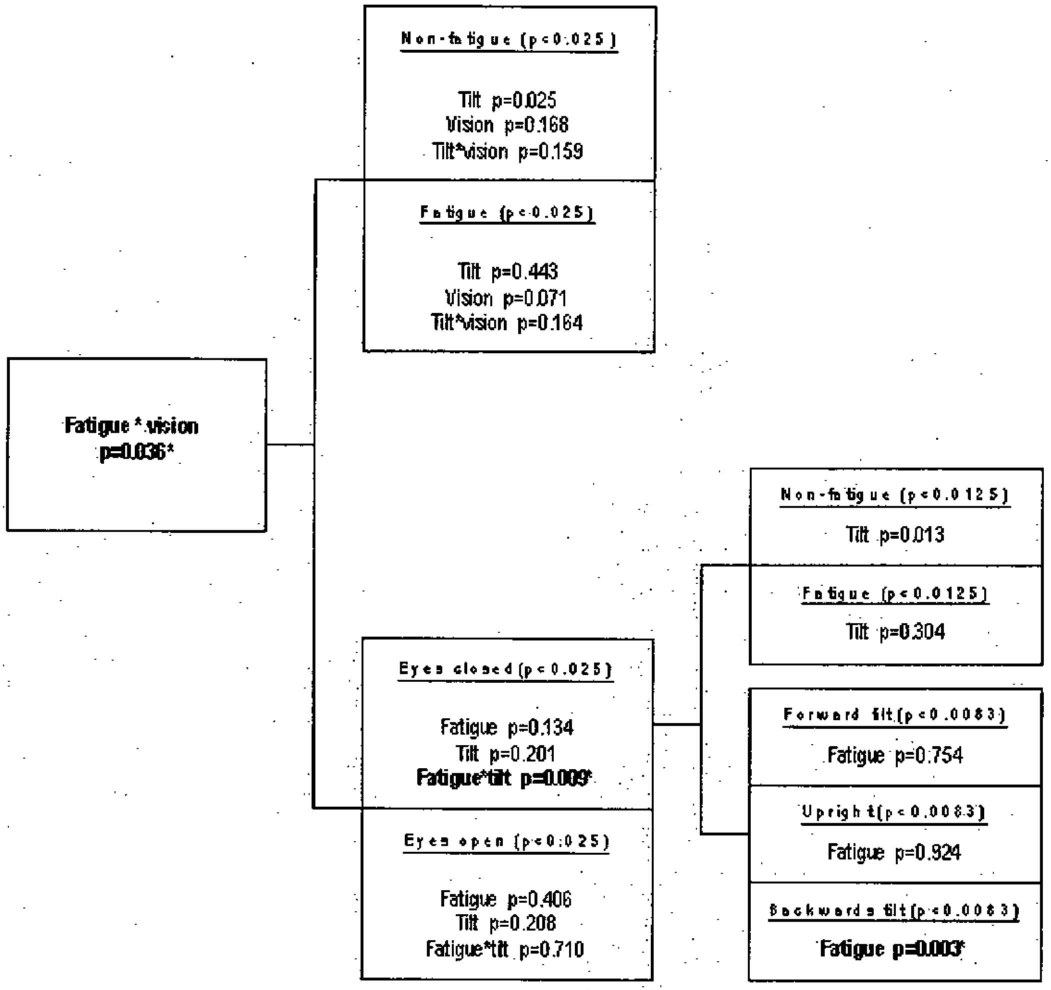


Figure 4.16. Separate repeated measures ANOVA for mean head protraction repositioning error (ME) in the local reference system. Bonferroni adjusted significance levels are indicated in brackets for each condition, and significant effects are marked in bold with an asterisk.

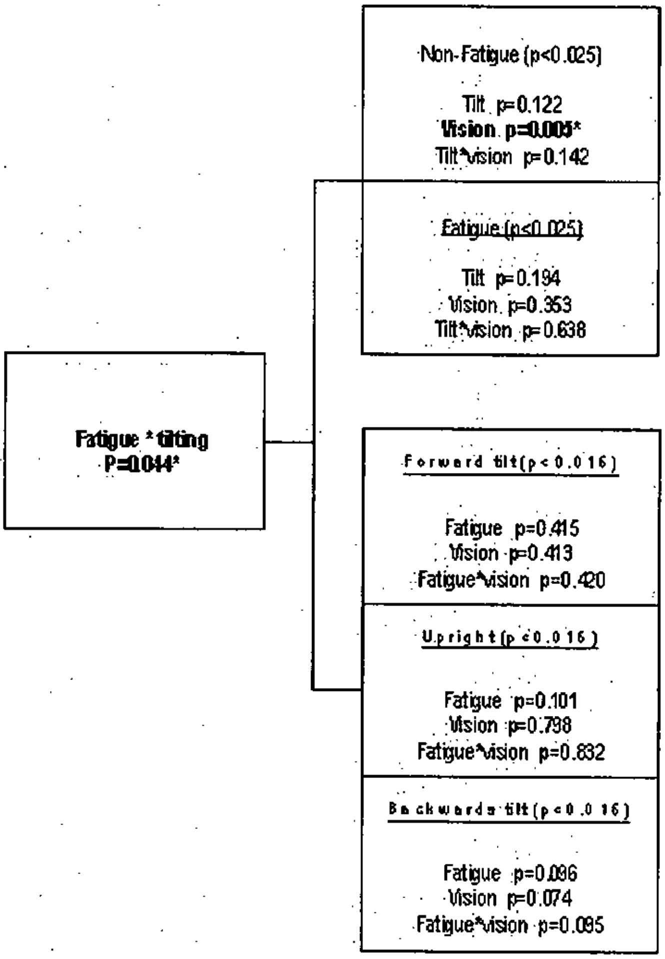


Figure 4.17. Separate repeated measures ANOVA for mean axial distraction repositioning error (ME) in the local reference system. Bonferroni adjusted significance levels are indicated in brackets for each condition, and significant effects are marked in bold with an asterisk

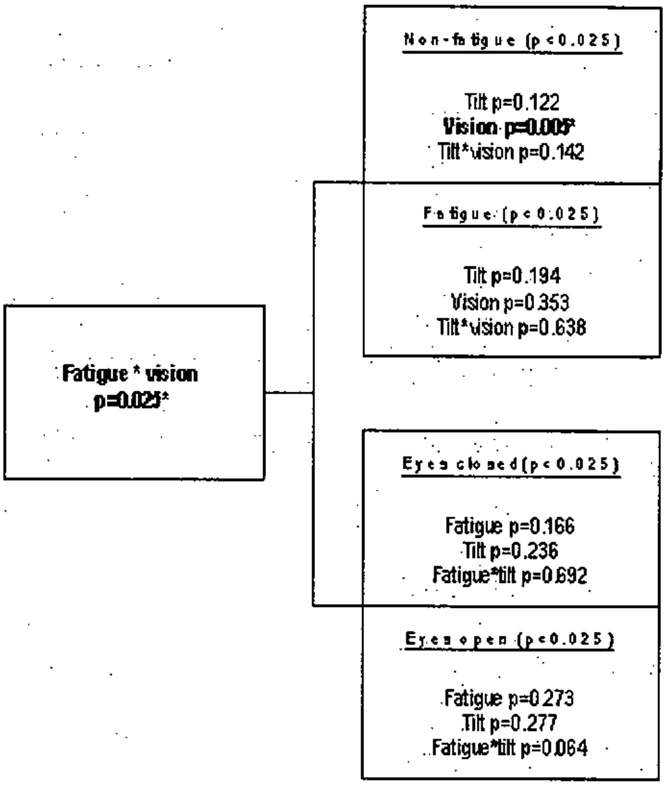


Fig 4.18. Separate repeated measures ANOVA for mean axial distraction repositioning error (ME) in the local reference system. Bonferroni adjusted significance levels are indicated in brackets for each condition, and significant effects are marked in bold with an asterisk

The mean head on trunk repositioning error in axial distraction compression showed a significant interaction between fatigue and tilting as well as fatigue and vision, and therefore the results were analyzed separately (figure 4.17 and 4.18). A significant effect of vision was found in the non-fatigued state, where the mean error with eyes closed (-0.2mm, p=0.005) was significantly lower than that with eyes open (0.6mm).

4.2 Repositioning absolute error (AE)

4.2.1 Angular repositioning AE in the global reference system

Visual status was found to have a significant main effect on the absolute repositioning error for axial rotation in the global reference system (table 4.6, figure 4.19, figure 4.20 and 4.21), with the absolute error with eyes closed (2.5^{o}) being significantly larger than the absolute error with eyes open (2.1^{o}). Other than this, no other significant effects of fatigue, chair tilt or vision were found for any of the other absolute angular repositioning errors in the global reference system, nor were any significant interactions between factors found.

Source of main effect / interaction	x-axis rotation	y-axis rotation	z-axis rotation
Fatigue	p=0.533	p=0.133	p=0.678
Tilting	p=0.279	p=0.596	p=0.233
Vision	p=0.086	p=0.233	p=0.019*
Fatigue * tilting	p=0.700	p=0.723	p=0.168
Fatigue * vision	p=0.620	p=0.986	p=0.767
Tilting * vision	p=0.274	p=0.482	p=0.915

Fatigue * tilting * vision	p=0.366	p=0.868	p=0.907

Table 4.6. Significances of main effects and interactions for the absolute angular error (AE) in the global reference system. P-values are marked with an asterisk where significant.

4.2.2 Angular repositioning AE in the local reference system

Similar to the results seen in the global reference system, a significant effect of vision was also found on the absolute rotational error in the local system (table 4.7, figure 4.22, figure 4.23 and 4.24). Again, the absolute error with eyes closed (2.3°) was significantly higher than that with eyes open (2.0°, p=0.036). No other significant main effects or interactions between factors were seen for the absolute angular repositioning errors in the local reference system.

Source of main effect / interaction	Flexion	Lateral flexion	Axial rotation
Fatigue	p=0.474	p=0.360	p=0.434
Tilting	p=0.303	p=0.157	p=0.731
Vision	p=0.094	p=0.155	p=0.036*
Fatigue * tilting	p=0.648	p=0.877	p=0.181
Fatigue * vision	p=0.577	p=0.608	p=0.308
Tilting * vision	p=0.358	p=0.828	p=0.762
Fatigue * tilting * vision	p=0.394	p=0.546	p=0.586

Table 4.7. Significances of main effects and interactions for the absolute angular error (AE) in the local reference system. P-values are marked with an asterisk where significant.

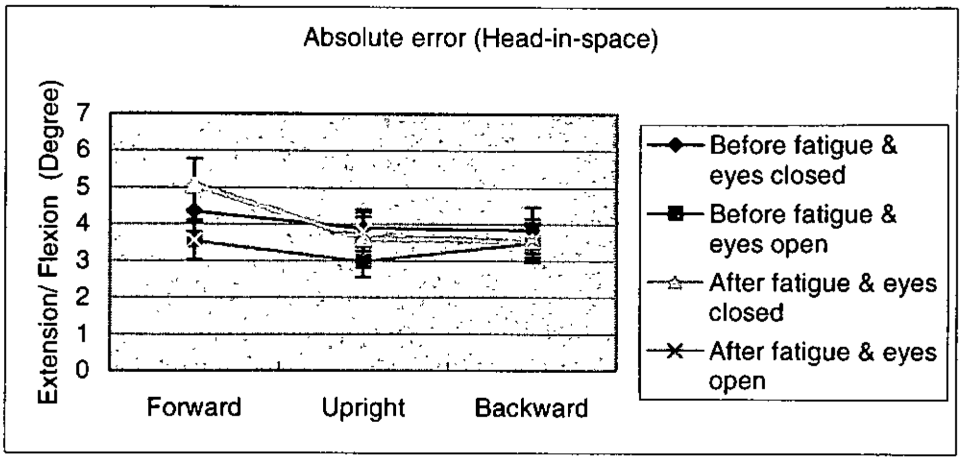


Figure 4.19. Absolute angular repositioning error (AE) around the x-axis in the global system for each chairback inclination under different fatigue and visual conditions.

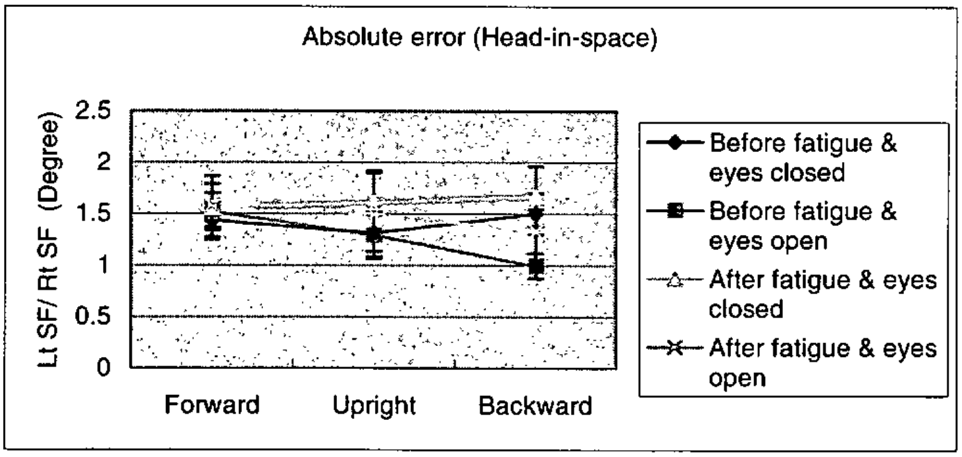


Figure 4.20. Absolute angular repositioning error (AE) around the y-axis in the global system for each chairback inclination under different fatigue and visual conditions.

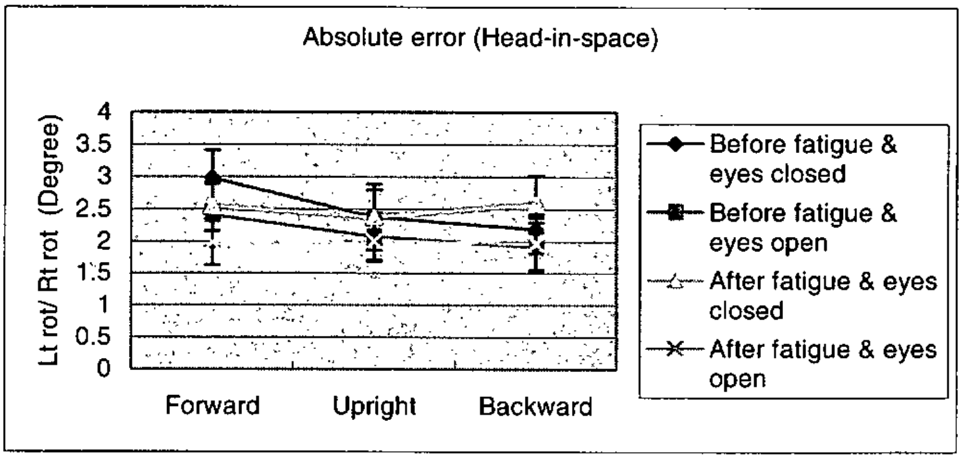


Figure 4.21. Absolute angular repositioning error (AE) around the z-axis in the global system for each chairback inclination under different fatigue and visual conditions.

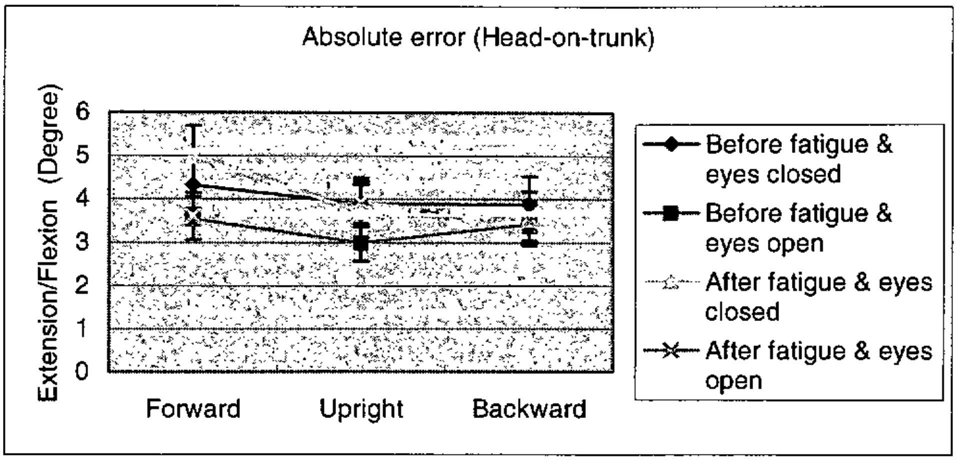


Figure 4.22. Absolute angular repositioning error (AE) around the x-axis in the local system for each chairback inclination under different fatigue and visual conditions.

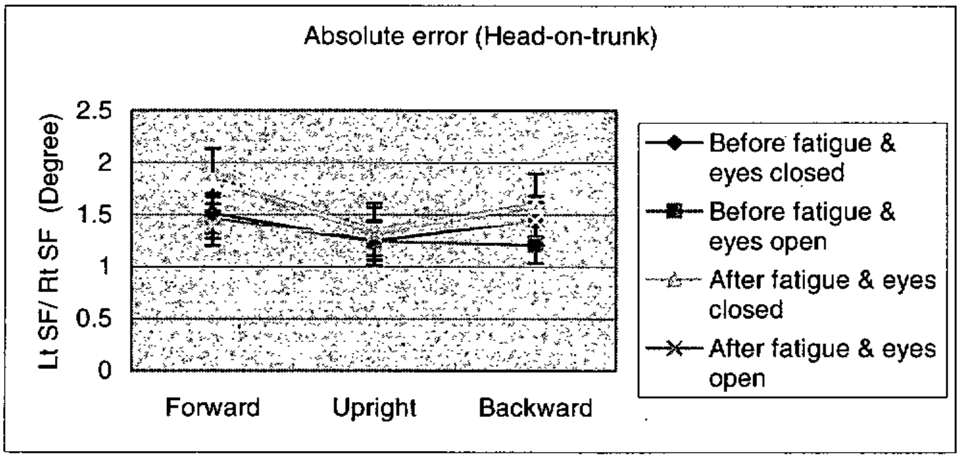


Figure 4.23. Absolute angular repositioning error (AE) around the y-axis in the local system for each chairback inclination under different fatigue and visual conditions.

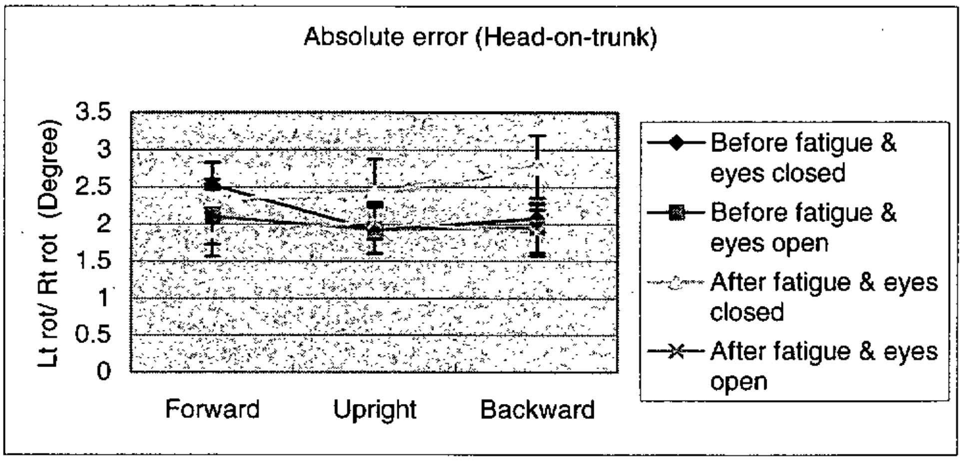


Figure 4.24. Absolute angular repositioning error (AE) around the z-axis in the local system for each chairback inclination under different fatigue and visual conditions.

4.2.3 Translational repositioning AE in the global reference system

Absolute errors in the global system showed a significant main effect of vision for translational repositioning error along the y-axis and a significant main effect of chairback inclination was also seen for translational errors along the z-axis (table 4.8, figure 4.25, figure 4.26 and 4.27). The absolute error along the y-axis with eyes closed (7.8mm) was significantly larger than that with eyes open (6.2mm, p=0.003). Post-hoc multiple comparisons for the effects of chairback inclination showed the absolute translational error along the z-axis in the upright position (2.2mm) to be significantly smaller than that for the forward inclined position (3.0mm, p=0.002), but not significantly different from that for the backward inclined position (2.5mm, p=0.690).

Source of main effect / interaction	x-axis translation	y-axis translation	z-axis translation
Fatigue	p=0.492	p=0.469	p=0.542
Tilting	p=0.498	p=0.537	P=0.034*
Vision	p=0.186	p=0.003*	P=0.056
Fatigue * tilting	p=0.562	p=0.693	p=0.150
Fatigue * vision	p=0.607	p=0.058	p=0.914
Tilting * vision	p=0.371	p=0.280	p=0.414
Fatigue * tilting * vision	p=0.449	p=0.487	p=0.318

Table 4.8. Significances of main effects and interactions for the absolute translational error (AE) in the global reference system. P-values are marked with an asterisk where significant.

4.2.4 Translational repositioning AE in the local reference system

Vision was also found to have a significant effect on the absolute translation error along the local system y-axis (protraction), being significantly higher with eyes closed

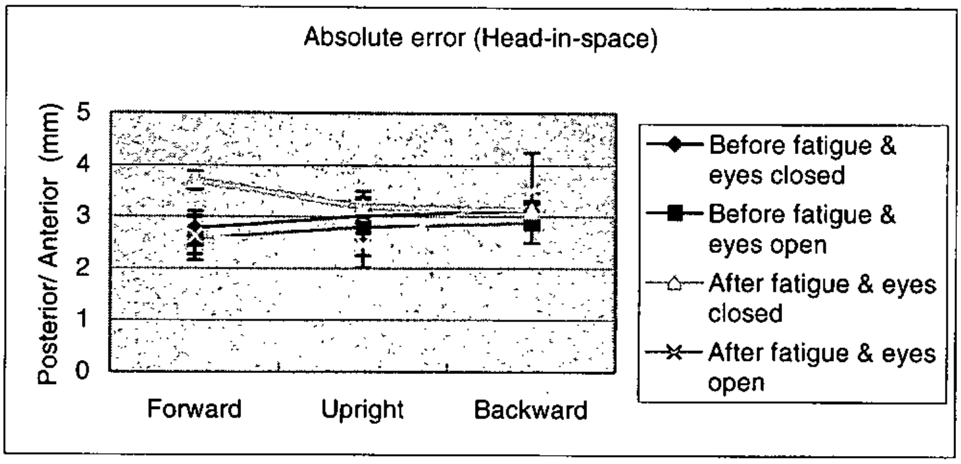


Figure 4.25. Absolute translational repositioning error (AE) around the x-axis in the global system for each chairback inclination under different fatigue and visual conditions.

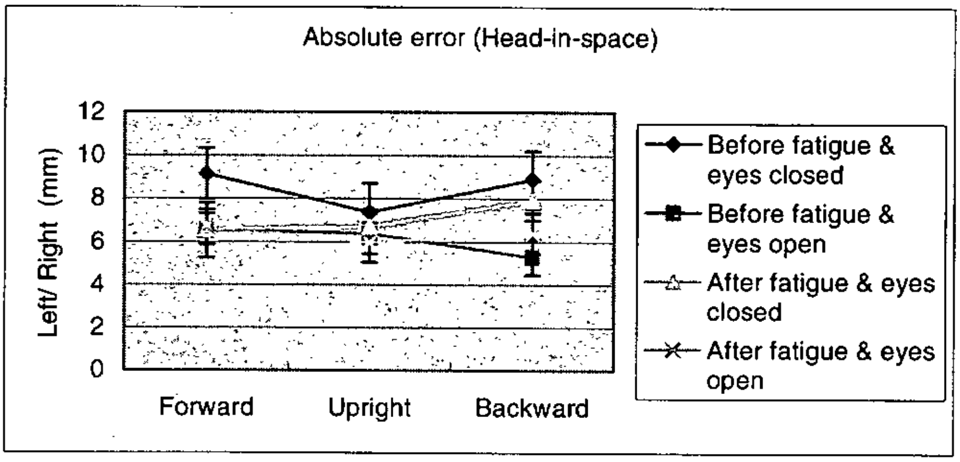


Figure 4.26. Absolute translational repositioning error (AE) around the y-axis in the global system for each chairback inclination under different fatigue and visual conditions.

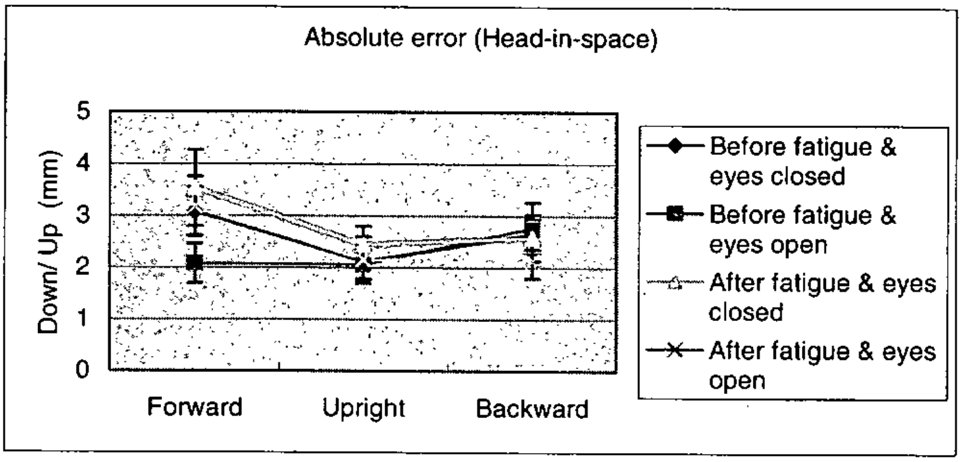


Figure 4.27. Absolute translational repositioning error (AE) around the z-axis in the global system for each chairback inclination under different fatigue and visual conditions.

(7.1mm) than with eyes open (6.1mm, p=0.026) (table 4.9, figure 4.28, figure 4.29 and 4.30). A significant effect of vision was similarly found for absolute translation error along the z-axis (distraction of the head), which was again higher with eyes closed (2.3mm) than with eyes open (2.1mm, p=0.026).

Source of main effect / interaction	Sidegliding	Protraction	Axial distraction
Fatigue	p=0.852	p=0.741	p=0.808
Tilting	p=0.872	P=0.833	p=0.246
Vision	p=0.207	p=0.026*	p=0.026*
Fatigue * tilting	p=0.999	p=0.795	p=0.219
Fatigue * vision	p=0.423	p=0.430	p=0.739
Tilting * vision	p=0.367	p=0.700	p=0.562
Fatigue * tilting * vision	p=0.427	p=0.563	p=0.619

Table 4.9. Significances of main effects and interactions for the absolute translational error (AE) in the local reference system. P-values are marked with an asterisk where significant.

4.3 Repositioning variability error (VE)

4.3.1 Angular repositioning VE in the global reference system

A significant effect of vision was found on the angular repositioning variability error around all three axis of the global system (table 4.10, figure 4.31). The angular variability error around the x-axis was significantly larger (p=0.004) with eyes closed (1.0°) than with eyes open (0.9°), and similarly significant results were found around the y-axis (2.1° with eyes closed, 1.9° with eyes open, p=0.006) and the z-axis (1.9° with eyes closed, 1.6° with eyes open, p=0.029). A significant effect of

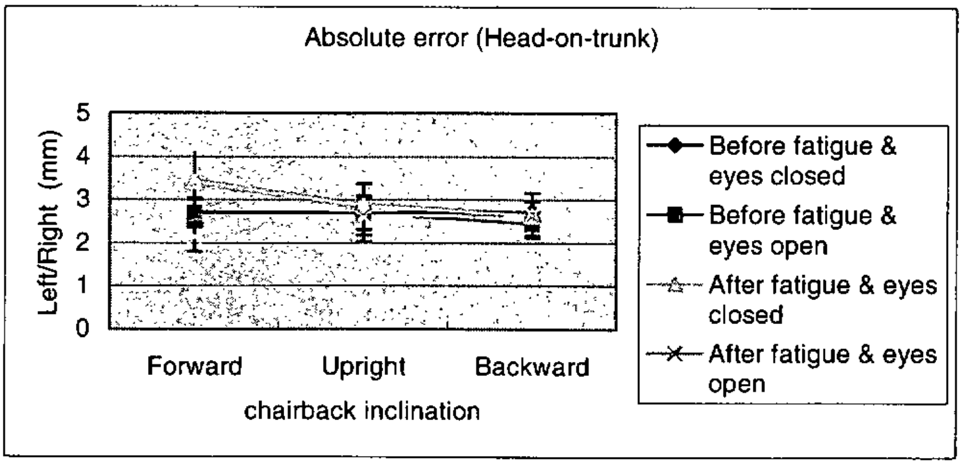


Figure 4.28. Absolute translational repositioning error (AE) around the x-axis in the local system for each chairback inclination under different fatigue and visual conditions.

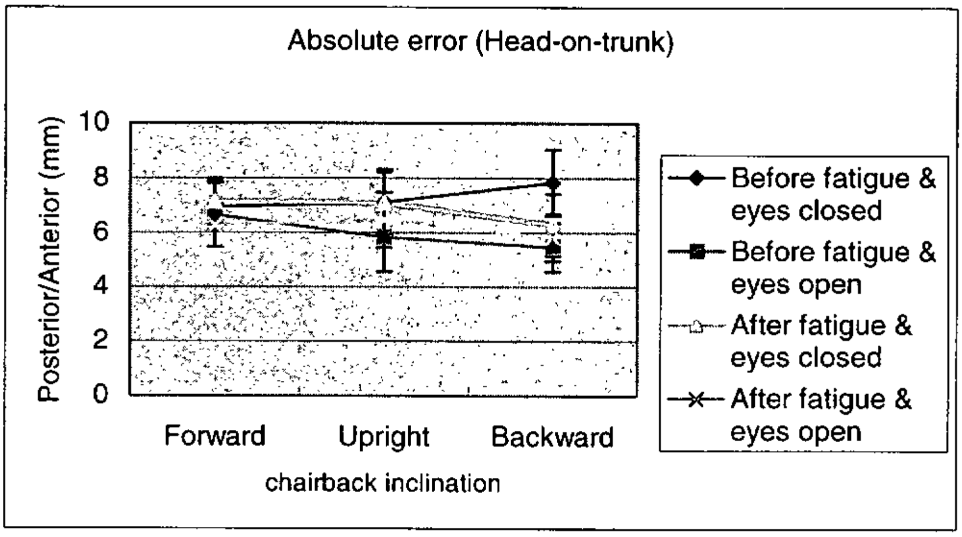


Figure 4.29. Absolute translational repositioning error (AE) around the y-axis in the local system for each chairback inclination under different fatigue and visual conditions.

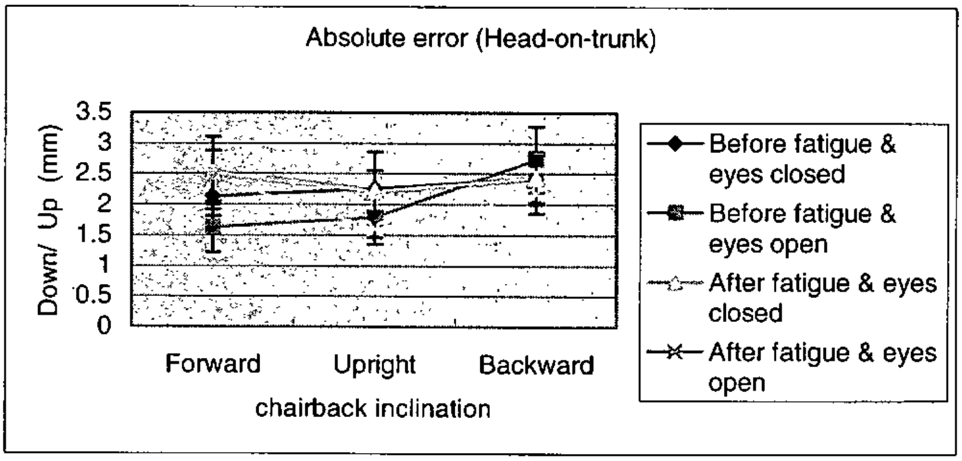


Figure 4.30. Absolute translational repositioning error (AE) around the z-axis in the local system for each chairback inclination under different fatigue and visual conditions.

fatigue was also found on the angular variability error around the z-axis (p=0.010), with the error before fatigue (1.8°) being significantly larger than that after fatigue (1.6°, p=0.010).

Source of main effect / interaction	x-axis rotation	y-axis rotation	z-axis rotation
Fatigue	p=0.346	p=0312.	p=0.010*
Tilting	p=0.676	p=0.441	p=0.840
Vision	p=0.004*	p=0.006*	p=0.029*
Fatigue * tilting	p=0.518	p=0.922	p=0.945
Fatigue * vision	p=0.704	p=0.245	p=0.578
Tilting * vision	p=0.453	p=0.442	p=0.799
Fatigue * tilting * vision	p=0.266	p=0.957	p=0.975

Table 4.10. Significances of main effects and interactions for the angular variability error (VE) in the global reference system. P-values are marked with an asterisk where significant.

4.3.2 Angular repositioning VE in the local reference system

A significant effect of vision was found on the variability error of the angular measurements along all axes in the local reference system (table 4.11, figure 4.32). Similar to the results for the global reference system, the variability errors with eyes closed (2.1°, 1.0° and 1.8° for flexion, lateral flexion, and axial rotation, respectively) were significantly larger than those with eyes open (1.9°, 0.9° and 1.4° for flexion, lateral flexion, and axial rotation, respectively). A significant effect of fatigue was also found on the angular variability error in rotation, which was again significantly larger before fatigue (1.7°) than after fatigue (1.5°, p=0.019).

Source of main effect / interaction	Flexion	Lateral flexion	Axial rotation
Fatigue	p=0.352	p=.138	p=0.019*
Tilting	p=0.554	p=0.408	p=0.607
Vision	p=0.001*	p=0.017*	p<0.001*
Fatigue * tilting	p=0.613	p=0.933	p=0.900
Fatigue * vision	p=0.685	p=0.390	p=0.348
Tilting * vision	p=0.397	p=0.605	p=0.559
Fatigue * tilting * vision	p=0.259	p=0.994	p=0.850

Table 4.11. Significances of main effects and interactions for the angular variability error (VE) in the local system. P-values are marked with an asterisk where significant.

4.3.3 Translational repositioning VE in the global reference system

Variability errors in translation along the x, y, and z axes of the global system also showed a significant effect of vision in all three axes (table 4.12, figure 4.33). The mean variability errors with eyes closed were 2.1mm, 4.2mm and 1.5mm in the x-, y- and z-axis, respectively. The same errors with eyes open were lower in all cases (1.8mm, 3.4mm and 1.2mm in the x-, y- and z-axis, respectively), and these differences were all significant (table 4.12).

Source of main effect / interaction	x-axis translation	y-axis translation	z-axis translation
Fàtigue	p=0.101	p=0.087	p=0.132
Tilting	p=0.661	p=0.734	p=0.442
Vision	P=0.004*	p=0.007*	P=0.004*
Fatigue * tilting	p=0.601	p=0.247	p=0.197

Fatigue * vision	p=0.983	p=0.254	p=0.267
Tilting * vision	p=0.228	p=0.327	p=0.951
Fatigue * tilting * vision	p=0.330	p=0.157	p=0.664

Table 4.12. Significances of main effects and interactions for the translational variability error (VE) in the global reference system. P-values are marked with an asterisk where significant.

4.3.4 Translational repositioning VE in the local reference system

Translational variability errors showed significant main effects of vision along the x and y of the local axes (table 4.13, figure 4.34), and the variability error for translation along the x-axis was significantly higher with the eyes closed (1.9mm) than with the eyes open (1.6mm, $p<0.001$). Similarly, the variability error for translation along the y-axis was significantly higher with the eyes closed (4.1mm) than with the eyes open (3.6mm, $p=0.013$). However, unlike the results for the global reference system, a significant interaction between fatigue and vision was found along the z-axis (axial distraction), and further analysis was therefore conducted.

Source of main effect / interaction	Sidegliding	Protraction	Axial distraction
Fatigue	p=0.205	p=0.065	p=0.066
Tilting	p=0.386	p=0.448	p=0.627
Vision	p<0.001*	p=0.013*	P=0.143
Fatigue * tilting	p=0.635	p=0.178	p=0.112
Fatigue * vision	p=0.466	p=0.097	p=0.030*
Tilting * vision	p=0.057	p=0.123	p=0.585
Fatigue * tilting * vision	p=0.527	p=0.241	p=0.897

Table 4.13. Significances of main effects and interactions for the translational variability error (VE) in the local reference system. P-values are marked with an asterisk where significant.

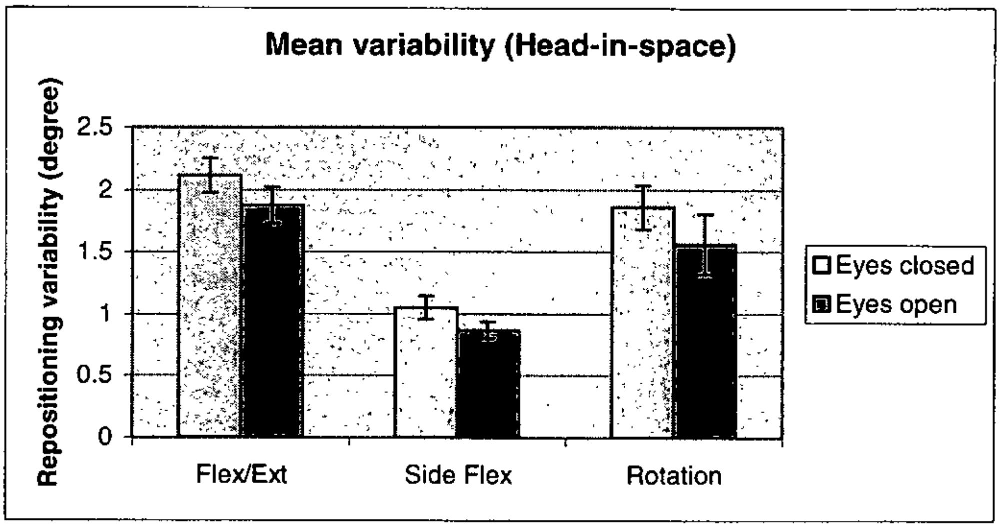


Figure 4.31. Angular repositioning variability error (VE) in the global system under different visual conditions.

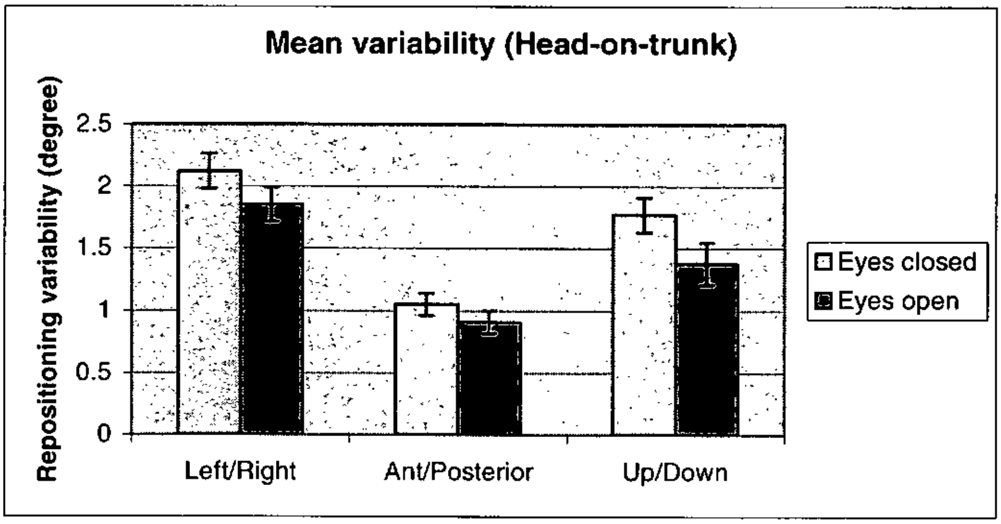


Figure 4.32. Angular repositioning variability error (VE) in the local system under different visual conditions.

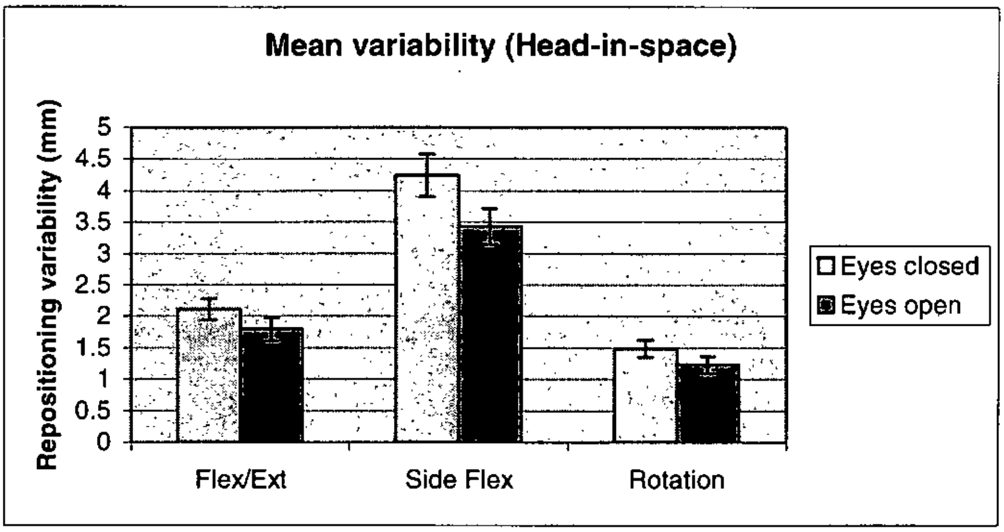


Figure 4.33. Translational repositioning variability error (VE) in the global system under different visual conditions.

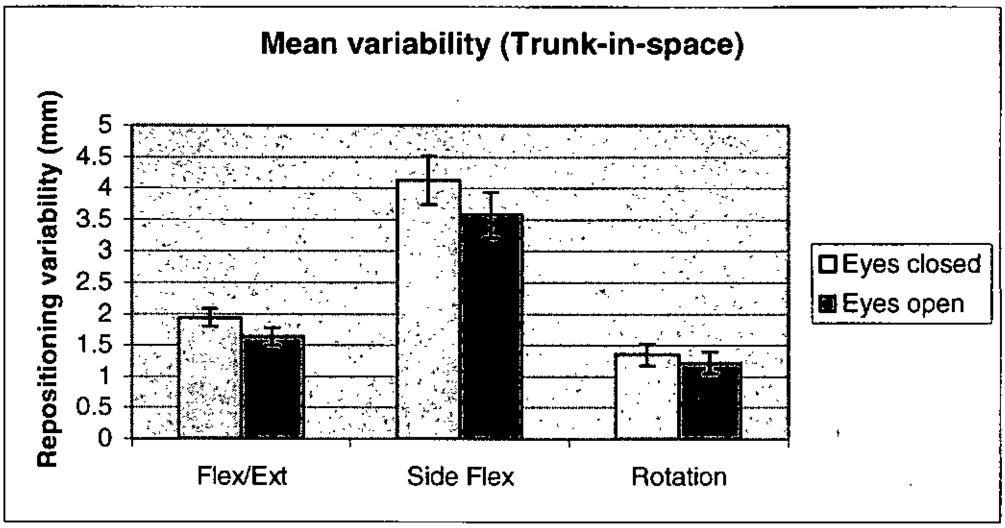


Figure 4.34. Translational repositioning variability error (VE) in the local system under different visual conditions.

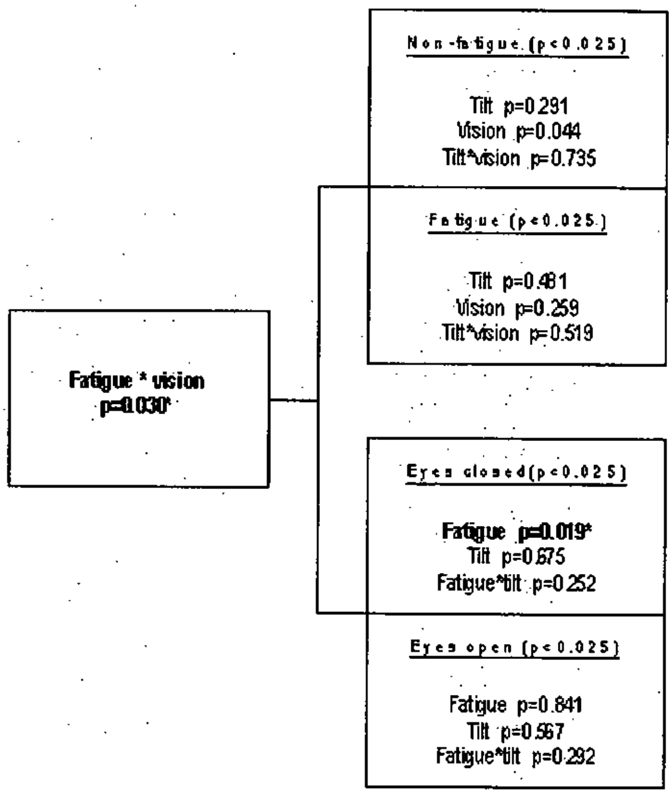


Figure 4.35. Separate repeated measures ANOVA for translational variability error (VE) along the z-axis in the local system. Bonferroni adjusted significance levels are indicated in brackets for each condition, and significant effects are marked in bold with an asterisk.

As shown in table 4.13, a significant interaction between fatigue and vision was found for the variability error along the z-axis of the local reference system (axial distraction), and therefore data was analyzed for fatigue and visual conditions separately (figure 4.35). The only significant effect found was that of fatigue in the eyes closed condition, where the variability error was significantly higher before fatigue (1.6mm) than after fatigue (1.1mm, p=0.019).

DISCUSSION

5.1 Effect of vision on repositioning accuracy and precision

Vision had very little effect on the angular repositioning accuracy of the head in space (ME in the global system) or of the head on the trunk (ME in the local system). A significant interaction was seen between fatigue, load and vision in the flexion repositioning accuracy (ME) in both of these reference systems, however. Further analysis showed the only significant effect of vision on angular repositioning accuracy to be for the head on trunk flexion angle before fatigue, which consistently undershot the memorized position with the eyes open (-1.8773°), but slightly overshot with eyes closed (0.8°). Overall, however, the memorized angular positions can be reproduced as accurately with the eyes closed as with the eyes open.

Vision has an effect on the absolute repositioning error in rotation of the head, both in space ($p=0.019$) and with respect to the trunk ($p=0.036$). In both cases, repositioning is closer to the memorized position when the vision is not occluded. However, as no significant effect of vision was seen in the accuracy (ME) of rotational repositioning of the head in either the global or local system, this indicates that there is no systematic undershoot or overshoot of the memorized rotation angle when the eyes are closed, but that the rotational repositioning is less precise when vision is occluded. This is demonstrated by the variability error (precision) in rotation, which is significantly higher for occluded vision both in the global and local reference systems. The precision for the other angles (flexion and lateral flexion) is also lower (VE is higher) when the vision is occluded, in both global and local reference frames. In general, vision has little effect on the ability to reproduce a certain angular position, but significantly affects the precision with which that angle can be reproduced in all three planes (flexion, lateral flexion and rotation).

When the translational repositioning errors were considered, vision again had a significant effect. The absolute repositioning errors in the y-axis were found to be higher in both global (towards the VDU) and local (head protraction) reference frames. Again, however, no effects of vision were found for the mean repositioning errors (repositioning accuracy) in either reference system along these directions, indicating that the same position is being reproduced when the eyes are closed, but less precisely. This is shown by the variability error along these directions, which is greater with occluded vision. A summary of the effects of vision are given in tables 5.1 and 5.2.

Table 5.1 Effect of Vision on the Head-in-space repositioning error (global reference system)

	Angular Repositioning Error	Translational Repositioning Error
x-axis	Closed > Open (VE)	Closed > Open (VE)
y-axis	Closed > Open (VE)	Closed > Open (AE) Closed > Open (VE)
z-axis	Closed > Open (AE) Closed > Open (VE)	Closed > Open (VE)

Table 5.2 Effect of Vision on the Head-in-space repositioning error (local reference system)

	Angular Repositioning Error	Translational Repositioning Error
x-axis	Closed > Open (VE)	Closed > Open (VE)

y-axis	Closed > Open (VE)	Closed > Open (AE) Closed > Open (VE)
z-axis	Closed > Open (AE) Closed > Open (VE)	Open > Closed (ME)[1] Closed > Open (AE)

[1] Non-fatigued only

For the maintenance of the head on neck posture, neck proprioceptors detect the orientation of head with respect to the trunk, while the vestibular apparatus and eyes detect the orientation and movement of the head alone (Guyton, 1986). Revel et al. (1991) also proposed that the proprioceptive system of the neck played a predominant role in cervicocephalic kinesthetic sensibility. In the present study, however, vision was found to have significant effects on the precision with which the memorized position can be reproduced in nearly all six degrees of freedom, both in space and with respect to the trunk. It is interesting to note that although vision is classified as exteroception, it seems to have an effect in controlling the head-on-trunk repositioning ability. If the head on trunk repositioning were dominated almost entirely by the proprioceptive and vestibular apparatus, as suggested (Guyton 1986, Revel et al. 1991), then vision should have little effect on the precision with which the memorized position is reproduced. However, while subjects were asked to direct their gaze on the VDU, no attempt was made to block the ambient mode of vision (peripheral vision), which is responsible for orientation and navigation during locomotion (Wade and Jones 1997). The ambient vision mode will include cues as to the position of the trunk, and may therefore aid in precisely reproducing the memorized position. This may also indicate that while one system may dominate, the integration of information from the triad of sensory systems (proprioception, vestibular and visual) may be the most important feature of the postural control system.

5.2 Effect of fatigue on repositioning accuracy and precision

Fatigue had no effect on the accuracy of angular repositioning of the memorized position, and the only significant effects of fatigue on the mean repositioning error were for translation along the x-axis of the global and local reference systems and translation along the y-axis (protraction) of the local reference system when the eyes were closed with chair tilted backwards. In these cases the accuracy of repositioning tended to overshoot following fatigue. Significant effects of fatigue were seen in the precision of rotational repositioning along the z-axis in both the local and global reference frames, however the repositioning was significantly more precise following fatigue of the upper trapezius muscles in these cases, as shown in tables 5.3 and 5.4.

Table 5.3 Effect of Fatigue on the Head-in-space Repositioning Error (Project to global)

	Angular Repositioning Error	Translational Repositioning Error
x-axis		Fatigued > Non-fatigued (ME)
z-axis	Non-fatigued > Fatigued (VE)	

Table 5.4 Effect of Fatigue on the Head-on-trunk Repositioning Error (Project to local)

	Angular Repositioning Error	Translational Repositioning Error
x-axis		Fatigued > Non-fatigued (ME)
y-axis		Fatigued > Non-fatigued[1] (ME)
z-axis	Non-fatigued > Fatigued (VE)	Fatigued > Non-fatigued[2] (VE)

[1] with Eyes closed and backward tilted position only

[2] with Eyes closed only

There is no obvious reason why the repositioning precision would be better following fatigue, but this may be due to motor behaviour rather than proprioceptive changes. Muscle stiffness is known to increase following fatigue (Gandevia et al., 1994). Despite the upper trapezius muscles themselves not acting as rotators of the neck (Williams, 1995), their increased stiffness after fatigue may restrict cervical movement such that the passive tension may keep the head in a more centred position. Interestingly, no effect was seen in other directions. Further studies are required to verify this observation.

5.3 Effect of tilting on repositioning accuracy and precision

Tilting had an overall main effect on accuracy (ME) of translation along the z-axis in the global frame. Significant interaction between fatigue, tilting and vision was found for translational ME in the global y-axis, but further analysis showed significant effects of tilt in particular conditions (with eyes open and closed, and before fatigue but not after).

Table 5.5 Effect of Backrest Tilting on the Head-in-space repositioning error (global reference system)

	Angular Repositioning Error	Translational Repositioning Error
y-axis		Backward > Forward (ME)[1] Backward > Upright (ME)[1] Backward > Forward (ME)[2] Backward > Forward (ME)[3] Backward > Upright (ME)[3]
z-axis		Forward > Upright (ME) Forward > Backward (ME) Forward > Upright (AE)

[1] Non-fatigue only

[2] Eyes closed only

[3] Eyes open only

Table 5.6 Effect of Backrest Tilting on the Head-on-trunk repositioning error (local reference system)

	Angular Repositioning Error	Translational Repositioning Error
x-axis	Forward > Upright (ME)[1]	

[1] Forward tilted and eyes closed only

5.4 Tilting of chair and ergonomic consideration

As far as the translational repositioning error of the head-in-space (towards VDU) was concerned, the mean error (ME) was less than 1 mm (i.e. –0.8 mm) in the non-fatigued situation with the chairback upright and eyes open. The mean error in this case was close to zero, reflecting the highly accurate postural repositioning sense and ability presented in normal subjects. However, statistical analysis revealed significant change in mean translational repositioning error once the chairback tilt angle was changed (p=0.001). Post-hoc comparisons using Bonferroni criteria showed the mean error in backward position (1.5 mm) was significantly higher than that in forward position (mean error –2.8mm, p=0.001) and upright position (mean error –1.6, p=0.028). Biomechanically, the increase in mean repositioning error associated with the backward position resembled the offset of the head from the support of the trunk, that is, an increase in the bending moment of the head on trunk. In the present study, however, the tilting did not have any significant effect on translational repositioning absolute and variability error in the same direction. In other words, there was systematic overshooting of the memorized position when the chair was tilted backward, but no decrease in repositioning precision. By and large, tilting of chair did have a significant effect on the head-in-space postural sense in terms of repositioning accuracy, but whether or not this will result in a clinically significant problem requires further investigation.

5.5 Effect of different reference systems

More or less the same effects were seen for the angular repositioning accuracy and precision whether the recordings were made in the global (head in space) or local (head on trunk) reference frames. This may explain why results from previous studies were comparable irrespective of what reference systems they were used. There are pro and cons in using either reference system. The head-in-space reference system allows biomechanical analysis of forces acting in reaction to gravity and the external environment, while local stresses in the cervical spine can be visualized easily from the head-on-trunk reference system. Both systems should be adopted until further investigation can tell which is better than the other.

5.6 Effect of different measuring directions

The direction in which the effects of fatigue, tilt and vision are monitored also appear to show differences. Significant main effects in mean error (i.e. accuracy) by tilt were observed only in translation along the z-axis of the global system (i.e. vertical direction). The observed change in repositioning error in the z-axis was probably largely due to the fluctuation in degree of co-contraction of the cervical muscles, but there is no obvious reason why this should be the case.

5.7 Comparison with previous results

The mean angular repositioning error (ME) in the non-fatigued condition with eyes closed and the chairback upright was –2.0° (standard deviation 3.92°), -0.1° (standard deviation 1.1°) and –0.1° (standard deviation 1.4°) in the sagittal, coronal and transverse planes, respectively, of the local reference system. These results were similar to those obtained under similar conditions by Christensen and Nilsson (1999).

5.8 Limitations

The present study is confined to normal subjects only. The feasibility of using the present protocol in testing patients requires further investigation.

Even though exclusion criteria are explicit, factors like vestibular integrity, which may affect the repositioning ability, have not been specifically evaluated by an otorhinolaryngologist.

The technique of measurement requires further improvement to detect the subtle changes in repositioning error. The tasks the subjects performed may not sufficiently challenge the proprioceptive system, since the reproduction of the "neutral" position is a fairly easy task frequently undertaken in daily life.

Fatigue in this case was limited to the upper trapezius muscles, but working in real life will involve fatigue of several muscle groups. In fact, the suboccipital muscles with their high density of proprioceptors may be a better alternative to upper trapezius fatigue, despite technical difficulties involved. McPartland et al. (1997) have studied the relationship between chronic neck pain, standing balance and suboccipital muscle atrophy. They hypothesized that patients with chronic neck pain have more somatic dysfunction in the cervical spine and atrophy of suboccipital muscles than normal subjects. Since suboccipital muscle have a high density of proprioceptors, they have also hypothesized that chronic neck pain patients will exhibit deficit in standing balance. They carried out a randomized, controlled, partially blind study to compare seven chronic neck pain patients with seven asymptomatic control subjects. Magnetic Resonance Imaging (MRI) has shown that chronic neck pain subjects have marked atrophy of the rectus capitii posterior major and minor muscles, including fatty infiltration. Moreover, force platform results have shown a decrease in standing balance of patients compared with control subjects (p=0.004). The results of the study suggest that there is a relationship between chronic pain, somatic dysfunction, muscle atrophy and standing balance. Also, they have hypothesized a degenerative cycle, initiated by chronic somatic dysfunction and followed by muscle atrophy. The lack of proprioceptive output from the atrophied muscles will cause reduction in the inhibition of nociception from the dorsal horn of the spinal cord, and hence result in chronic pain and deficit in standing balance. The indirect evidence of the relationship between chronic neck pain, standing balance and suboccipital muscle atrophy sheds some light on the role of the suboccipital muscles in the proprioception system of the neck. Further research should be conducted on the effect of fatigue of the suboccipital muscles in head repositioning ability.

Repositioning ability is only part of the measure of proprioception. A large scale study will be required to investigate the correlation of the findings between repositioning ability, passive movement threshold or directional movement sense methods in assessing neck proprioception.

Testing subjects in a controlled experimental environment may generate results different from those in real life situations. Transient tilting of chair and short duration fatiguing protocol may not be sufficient to resemble real working situations.

5.9 Recommendations for future work

Clinically, some patients with cervical pain may still complain of neck discomfort even after a long period of rehabilitation. Objectively, they may have no deficit in range of motion (ROM), muscle power and sensation and yet they may have persistent sub-clinical postural related symptoms. Indeed, it is hypothesized that the origin of pain without accompanying tissue pathology would demand an explanation possibly similar to the sensory conflict theory of motion sickness (Harris, 1999). Disorganized or inappropriate cortical representation of proprioception may falsely signal active region of the cortex, which is sensitive to incongruence between motor intention, awareness of movement and visual feedback (Harris, 1999). The interaction of the triads of head postural control and the intimate relationship between proprioception and pain has been largely unexplored in the past. The present study has provided a systemic way of investigation of different factors which may affect the head postural control in terms of repositioning accuracy. The present methodology could be extended to patient groups with different pathologies like postural cervical pain syndrome to address their proprioceptive deficit and eventually design a better treatment strategy. Besides, the result of the present study suggested that the measure of proprioceptive ability is a potential tool for investigating and evaluating different ergonomic conditions.

CONCLUSION

Vision had very little effect on the accuracy of angular repositioning of the head in space or the head on trunk, however the precision of repositioning is significantly lower after vision is occluded in both global and local reference systems. In general, vision has little effect on the ability to reproduce a certain angular position, but significantly affects the precision with which that angle can be reproduced in all three planes (sagittal, coronal and transverse).

Fatigue of the upper trapezius muscles had no effect on the angular repositioning accuracy, but the angular repositioning variability error along vertical and axial distraction axes were significantly reduced after fatigue. On the other hand, the mean reproduced position tended to overshoot the memorized position along the x-axis of the local (sidegliding) and global reference systems following fatigue.

Unlike fatigue, tilting of the chair back had a significant effect on the translational repositioning accuracy along the y-axis and z-axis of global system (vertical axis). Results also revealed a significant change in mean translational repositioning error along the global y-axis (towards VDU) with changes in chair back inclination. The significant mean repositioning error in this direction indicates a change in the centre of gravity of the head with respect to the base of support at the trunk, and the clinical and ergonomic implications of this finding warrants further investigation.

More or less the same effects were seen for the angular repositioning accuracy and precision whether the recordings were made in the global (head in space) or local (head on trunk) reference frames. While both systems have their relative advantages, it is recommended that both systems should be used in obtaining a complete understanding of the repositioning ability of the cervical spine.

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APPENDIX A

Exclusion Criteria

- Episode of neck pain after trauma (e.g. whiplash)
- History of cervical injury or trauma
- Cervical radiculopathy and/or myelopathy
- Inflammatory arthritis involving cervical spine
- Tumour or infection involving cervical spine
- Vertebobasilar artery insufficiency (VBI)
- Neurologic disease (e.g. multiple sclerosis, Parkinson's disease, syringomyelia)
- Congenital anomalies involving cervical spine
- Patients involving in litigation or compensatory claims
- History of dizziness or vertigo
- Undergo current treatment for any other musculoskeletal complaint
- Systemic disease (e.g. diabetes mellitus or hypertension)

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APPENDIX B

Jockey Club Rehabilitation Engineering Centre
The Hong Kong Polytechnic University
Hung Hom, Kowloon, HKSAR
Tel: 27667674

Consent Form

I, ____________________________(name), the undersigned, hereby consent to participate in as a subject for the research project "To Investigate the Effect of Different Factors on the Proprioception of the Cervical spine in Patients with Cervical Symptoms". I have the right to understand the effects of the experimental procedure and have the right to discontinue my participation anytime with no reasons given, even during the experiment. I further realize that any finding of the study will only be used for research and will be the property of the Jockey Club Rehabilitation Engineering Centre of The Hong Kong Polytechnic University.

Subject's signature____________________________
Name in block letter___________________________

Witness's signature___________________________
Name in block letter___________________________

Date______________________

APPENDIX C

To Investigate the Effect of Different Factors on the Proprioception of the Cervical spine in Patients with Cervical Symptoms

Jockey Club Rehabilitation Engineering Centre
The Hong Kong Polytechnic University

Subject's Information Sheet

Details of the study

The purpose of this study is to assess the effect of muscle fatigue on the postural control of the neck.

During the experiment, the position of the head and trunk will be monitored by the video movement analysis system with reflective markers attached onto the skins of the respective regions. Initially, the subject was randomly assigned to blindfolded or not blindfolded. Then, the subject will be asked to memorize a particular posture and then reproduce it after a set of neck movement. This repositioning ability test will be repeated 10 times each with chair in three different tilting positions and in two conditions (i.e. blindfolded or not blindfolded). Totally, the subject needs to perform 60 times (10 x 3 x 2 = 60). Thereafter a set of isometric shoulder exercise will be done for about 3 min., until fatigue. The EMG data will be collected via surface electrodes, which attached onto the skins of neck and shoulder. Immediately after the fatiguing exercises, the repositioning ability test will be repeated again for three times with chair in three different tilting positions and in two conditions (i.e. another 60 times).

Rights

- There is no harmful effect to the subjects. Some subjects may experience muscle soreness after testing, which will be subsided after one or two days.
- You have the right to withdraw from the study with no reasons given, at any time, even during the experiment.

- The research is conducted by Mr. Wong Fu Yan, Thomas, Dr. Chow Hung Kay, Daniel and Dr. Cheung Man Chee, Kenneth. It is supported by the Hong Kong Polytechnic University Departmental Research Committee. All information will be kept confidential. You are free to contact the Hong Kong Polytechnic University Departmental Research Committee directly for any inquiry or complaints.

Procedure

1. System calibration*
2. Skin preparation
3. Markers and electrodes setup
4. Randomization
5. Memorize "the" neck posture
6. A set of neck movement
7. Reproduce "the memorized" neck posture
8. Repeat step 5-7 immediately without rest for 9 more times
9. Rest for 1 min
10. Repeat step 5-9 with 5 other conditions (i.e. 3 tilting positions of chair; eye open or closed)
11. Isometric shoulder exercise for about 3 min.
12. Repeat step 5-10 immediately after isometric shoulder exercise
13. Reset neutral neck posture
14. Full range of movement measured

Thank you for your kind support and assistance

APPENDIX D

Reflective markers placement

Real Marker	**Placement**	**Coordinates**
P$_1$	Tragus of left ear	(x_1, y_1, z_1)
P$_2$	Tragus of right ear	(x_2, y_2, z_2)
P$_3$	Inferior margin of left orbit (at the horizontal level of P1 & P2)	(x_3, y_3, z_3)
P$_4$	Left coracoid process	(x_4, y_4, z_4)
P$_5$	Right coracoid process	(x_5, y_5, z_5)
P$_6$	Sternal notch (at the horizontal level of P4 & P5)	(x_6, y_6, z_6)

Imaginary Marker	**Description**	
P$_H$	Origin of the head	(x_H, y_H, z_H)
P$_T$	Origin of the trunk	(x_B, y_B, z_B)

Let $\overrightarrow{Vx}$ be $\overrightarrow{P_1P_2}$,then $\overrightarrow{Vx} = \dfrac{\overrightarrow{P_1P_2}}{|P_1P_2|}$

If $\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3} = \overrightarrow{Vz}$, then $\overrightarrow{Vz} = \dfrac{\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3}}{\left|\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3}\right|}$

If

$$\overrightarrow{Vy} = \overrightarrow{Vz} \times \overrightarrow{Vx}$$

Then,

$$[\mathbf{M_H}] = \begin{bmatrix} \mathbf{V}_{xx} & \mathbf{V}_{xy} & \mathbf{V}_{xz} \\ \mathbf{V}_{yx} & \mathbf{V}_{yy} & \mathbf{V}_{yz} \\ \mathbf{V}_{zx} & \mathbf{V}_{zy} & \mathbf{V}_{zz} \end{bmatrix}$$

where $[\mathbf{M_H}]$ is the local coordinate system of the head

Similarly,

Let $\overrightarrow{Ux}$ be $\overrightarrow{P_4P_5}$,then $\overrightarrow{Ux} = \dfrac{\overrightarrow{P_4P_5}}{|P_4P_5|}$

If $\overrightarrow{P_4P_5} \times \overrightarrow{P_4P_6} = \overrightarrow{Uz}$, then $\overrightarrow{Uz} = \dfrac{\overrightarrow{P_4P_5} \times \overrightarrow{P_4P_6}}{\left|\overrightarrow{P_4P_5} \times \overrightarrow{P_4P_6}\right|}$

If

$$\overrightarrow{Uy} = \overrightarrow{Uz} \times \overrightarrow{Ux}$$

then,

$$[\mathbf{M_B}] = \begin{bmatrix} \mathbf{U}_{xx} & \mathbf{U}_{xy} & \mathbf{U}_{xz} \\ \mathbf{U}_{yx} & \mathbf{U}_{yy} & \mathbf{U}_{yz} \\ \mathbf{U}_{zx} & \mathbf{U}_{zy} & \mathbf{U}_{zz} \end{bmatrix}$$

where $[\mathbf{M_B}]$ is the local coordinate system of the body

At t = 0,

$$[\mathbf{M_H}]_0 = \begin{bmatrix} \mathbf{V}_{xx0} & \mathbf{V}_{xy_0} & \mathbf{V}_{xz_0} \\ \mathbf{V}_{yx_0} & \mathbf{V}_{yy_0} & \mathbf{V}_{yz_0} \\ \mathbf{V}_{zx_0} & \mathbf{V}_{zy_0} & \mathbf{V}_{zz_0} \end{bmatrix}$$

$$[\mathbf{M_B}]_0 = \begin{bmatrix} \mathbf{U}_{xx_0} & \mathbf{U}_{xy_0} & \mathbf{U}_{xz_0} \\ \mathbf{U}_{yx_0} & \mathbf{U}_{yy_0} & \mathbf{U}_{yz_0} \\ \mathbf{U}_{zx0} & \mathbf{U}_{zy_0} & \mathbf{U}_{zz_0} \end{bmatrix}$$

At t = t,

$$[\mathbf{M_H}]_t = \begin{bmatrix} \mathbf{V}_{xxt} & \mathbf{V}_{xy_t} & \mathbf{V}_{xz_t} \\ \mathbf{V}_{yx_t} & \mathbf{V}_{yy_t} & \mathbf{V}_{yz_t} \\ \mathbf{V}_{zx_t} & \mathbf{V}_{zy_t} & \mathbf{V}_{zz_t} \end{bmatrix}$$

$$[\mathbf{M_B}]_t = \begin{bmatrix} \mathbf{U}_{xx_t} & \mathbf{U}_{xy_t} & \mathbf{U}_{xz_t} \\ \mathbf{U}_{yx_t} & \mathbf{U}_{yy_t} & \mathbf{U}_{yz_t} \\ \mathbf{U}_{zxt} & \mathbf{U}_{zy_t} & \mathbf{U}_{zz_t} \end{bmatrix}$$

Based on the Chow's angle (Chow, 1994),

At t = 0,

$$F_{G0} = \tan^{-1}(V_{zy_0}/V_{zz_0}) - \tan^{-1}(U_{zy_0}/U_{zz_0})$$

$$S_{G0} = \tan^{-1}(V_{zx_0}/V_{zz_0}) - \tan^{-1}(U_{zx_0}/U_{zz_0})$$

$$T_{G0} = \tan^{-1}\frac{(V_{zy_0})(V_{zy_0}V_{yx_0} - V_{zx_0}V_{yy_0}) - V_{zx_0}(V_{zx_0}V_{xy_0} - V_{zy_0}V_{xx_0})}{(V_{zy_0})(V_{zy_0}V_{yx_0} - V_{zx_0}V_{yy_0}) + V_{zx_0}(V_{zx_0}V_{xy_0} - V_{zy_0}V_{xx_0})}$$
$$- \tan^{-1}\frac{(U_{zy_0})(U_{zy_0}U_{yx_0} - U_{zx_0}U_{yy_0}) - U_{zx_0}(U_{zx_0}U_{xy_0} - U_{zy_0}U_{xx_0})}{(U_{zy_0})(U_{zy_0}U_{yx_0} - U_{zx_0}U_{yy_0}) + U_{zx_0}(U_{zx_0}U_{xy_0} - U_{zy_0}U_{xx_0})}$$

At t = t,

$$F_{Gt} = \tan^{-1}(V_{zy_t}/V_{zz_t}) - \tan^{-1}(U_{zy_t}/U_{zz_t})$$

$$S_{Gt} = \tan^{-1}(V_{zx_t}/V_{zz_t}) - \tan^{-1}(U_{zx_t}/U_{zz_t})$$

$$T_{Gt} = \tan^{-1}\frac{(V_{zy_t})(V_{zy_t}V_{yx_t} - V_{zx_t}V_{yy_t}) - V_{zx_t}(V_{zx_t}V_{xy_t} - V_{zy_t}V_{xx_t})}{(V_{zy_t})(V_{zx_t}V_{xy_t} - V_{zy_t}V_{xx_t}) + V_{zx_t}(V_{zy_t}V_{yx_t} - V_{zx_t}V_{yy_t})}$$

$$- \tan^{-1}\frac{(U_{zy_t})(U_{zy_t}U_{yx_t} - U_{zx_t}U_{yy_t}) - U_{zx_t}(U_{zx_t}U_{xy_t} - U_{zy_t}U_{xx_t})}{(U_{zy_t})(U_{zy_t}U_{yx_t} - U_{zx_t}U_{yy_t}) + U_{zx_t}(U_{zx_t}U_{xy_t} - U_{zy_t}U_{xx_t})}$$

If both F and S are equal to zero, then

$$T_{G0} = \tan^{-1}(V_{xy_0} / V_{xx_0}) - \tan^{-1}(U_{xy_0} / U_{xx_0})$$
$$T_{Gt} = \tan^{-1}(V_{xy_t} / V_{xx_t}) - \tan^{-1}(U_{xy_t} / U_{xx_t})$$

With reference to global system, where repositioning error between t=t and t=0,

Angle of Flexion (Global): $\mathbf{F_{Global} = F_{Gt} - F_{G0}}$

Angle of Side Bending (Global): $\mathbf{S_{Global} = S_{Gt} - S_{G0}}$

Angle of Rotation (Global): $\mathbf{T_{Global} = T_{Gt} - T_{G0}}$

F: "+" => Towards bottom of VDU, "-" => Towards top of VDU
S: "+" => To right lower corner of VDU, "-" => To left lower corner of VDU
T: "+" => Towards left of VDU, "-" => Towards right of VDU

Relative orientation of the Head and the Body can be expressed as follows:

$$[\mathbf{M}_{\mathbf{H}}] = [\mathbf{R}_{\mathbf{B/H}}][\mathbf{M}_{\mathbf{B}}]$$

where $[\mathbf{R}_{\mathbf{B/H}}]$ is the orthogonal matrix describing the relative orientation of head on trunk

At t = 0

$$[\mathbf{M}_{\mathbf{H}}]_0 = [\mathbf{R}_{\mathbf{B/H}}]_0[\mathbf{M}_{\mathbf{B}}]_0$$

$$[\mathbf{R}_{\mathbf{B/H}}]_0 = [\mathbf{M}_{\mathbf{H}}]_0[\mathbf{M}_{\mathbf{B}}]_0^T$$

At t = t

$$[\mathbf{M}_{\mathbf{H}}]_t = [\mathbf{R}_{\mathbf{B/H}}]_t[\mathbf{M}_{\mathbf{B}}]_t$$

$$[\mathbf{R}_{\mathbf{B/H}}]_t = [\mathbf{M}_{\mathbf{H}}]_t[\mathbf{M}_{\mathbf{B}}]_t^T$$

Let

$$[\mathbf{R}_{\mathbf{B/H}}]_0 = \begin{bmatrix} \mathbf{R}_{11_0} & \mathbf{R}_{12_0} & \mathbf{R}_{13_0} \\ \mathbf{R}_{21_0} & \mathbf{R}_{22_0} & \mathbf{R}_{23_0} \\ \mathbf{R}_{31_0} & \mathbf{R}_{32_0} & \mathbf{R}_{33_0} \end{bmatrix}$$

and

$$[\mathbf{R}_{\mathbf{B/H}}]_t = \begin{bmatrix} \mathbf{R}_{11_t} & \mathbf{R}_{12_t} & \mathbf{R}_{13_t} \\ \mathbf{R}_{21_t} & \mathbf{R}_{22_t} & \mathbf{R}_{23_t} \\ \mathbf{R}_{31_t} & \mathbf{R}_{32_t} & \mathbf{R}_{33_t} \end{bmatrix}$$

Based on the Chow's angle (Chow, 1994),

At t = 0,

$$F_{L0} = \tan^{-1}(\mathbf{R}_{32_0}/\mathbf{R}_{33_0})$$

$$S_{L0} = \tan^{-1}(\mathbf{R}_{31_0}/\mathbf{R}_{33_0})$$

$$T_{L0} = \tan^{-1}\frac{(R_{32_0})(R_{32_0}R_{21_0} - R_{31_0}R_{22_0}) - R_{31_0}(R_{31_0}R_{12_0} - R_{32_0}R_{11_0})}{(R_{32_0})(R_{31_0}R_{12_0} - R_{32_0}R_{11_0}) + R_{31_0}(R_{32_0}R_{21_0} - R_{31_0}R_{22_0})}$$

At t = t,

$$F_{Lt} = \tan^{-1}(\mathbf{R}_{32_t}/\mathbf{R}_{33_t})$$

$$S_{Lt} = \tan^{-1}(\mathbf{R}_{31_t}/\mathbf{R}_{33_t})$$

$$T_{Lt} = \tan^{-1}\frac{(R_{32_t})(R_{32_t}R_{21_t} - R_{31_t}R_{22_t}) - R_{31_t}(R_{31_t}R_{12_t} - R_{32_t}R_{11_t})}{(R_{32_t})(R_{31_t}R_{12_t} - R_{32_t}R_{11_t}) + R_{31_t}(R_{32_t}R_{21_t} - R_{31_t}R_{22_t})}$$

If both F and S are equal to zero, then

$$T_{L0} = \tan^{-1}(\mathbf{R}_{12_0}/\mathbf{R}_{11_0})$$

$$T_{Lt} = \tan^{-1}(\mathbf{R}_{12_t}/\mathbf{R}_{11_t})$$

With reference to local system, where repositioning error between t=t and t=0,

Angle of Flexion (Local): $F_{Local} = F_{Lt} - F_{L0}$

Angle of Side Bending (Local): $S_{Local} = S_{Lt} - S_{L0}$
Angle of Rotation (Local): $T_{Local} = T_{Lt} - T_{L0}$

F: "+" => flexion, "-" => extension
S: "+" => right side bending, "-" => left side bending
T: "+" => left axial rotation, "-" => right axial rotation

Let $P_H(x_H, y_H, z_H)$ be the centroid of $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$,

Then

$$x_H = (x_1 + x_2)/3$$
$$y_H = (y_1 + y_2)/3$$
$$z_H = (z_1 + z_2)/3$$

Let $P_B(x_B, y_B, z_B)$ be the centroid of $P_4(x_4, y_4, z_4)$, $P_5(x_5, y_5, z_5)$, and $P_6(x_6, y_6, z_6)$

Then

$$x_B = (x_4 + x_5 + x_6)/3$$
$$y_B = (y_4 + y_5 + y_6)/3$$
$$z_B = (z_4 + z_5 + z_6)/3$$

Translational deviation of the P_H from P_B at any time instant is

$$x_G = x_H - x_B$$
$$y_G = y_H - y_B$$
$$y_G = y_H - y_B$$

At t = 0, $x_{G_0} = x_{H_0} - x_{B_0}$

$$y_{G_0} = y_{H_0} - y_{B_0}$$
$$z_{G_0} = z_{H_0} - z_{B_0}$$

At t = t, $x_{G_t} = x_{H_t} - x_{B_t}$

$$y_{G_t} = y_{H_t} - y_{B_t}$$
$$z_{G_t} = z_{H_t} - z_{B_t}$$

With reference to global system, where repositioning error between t=t and t=0,
Translation x-axis (Global): $x_{Global} = x_{G_t} - x_{G_0}$
Translation y-axis (Global): $y_{Global} = y_{G_t} - y_{G_0}$
Translation z-axis (Global): $z_{Global} = z_{G_t} - z_{G_0}$
x-axis (Global): "+" => Towards right of VDU, "-" => Towards left of VDU
y-axis (Global): "+" => Towards VDU, "-" => Away from VDU
z-axis (Global): "+" => Up, "-" => Down
Since translational deviation of the P_H from P_B at any time instant is

$$x_G = x_H - x_B$$
$$y_G = y_H - y_B$$
$$y_G = y_H - y_B$$

Translational deviation of the P_H from P_B projected to the local coordinate system of the body at any time instant is

$$\begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} = [M_B] \bullet \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix}$$ where $[M_B]$ is the local coordinate system of the body

$$\begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} = \begin{bmatrix} U_{xx} & U_{xy} & U_{xz} \\ U_{yx} & U_{yy} & U_{yz} \\ U_{zx} & U_{zy} & U_{zz} \end{bmatrix} \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} = \begin{bmatrix} U_{xx}x_G + U_{xy}y_G + U_{xz}z_G \\ U_{yx}x_G + U_{yy}y_G + U_{yz}z_G \\ U_{zx}x_G + U_{zy}y_G + U_{zz}z_G \end{bmatrix}$$

At t=0 $$\begin{bmatrix} x_{L_0} \\ y_{L_0} \\ z_{L_0} \end{bmatrix} = [M_B]_0 \bullet \begin{bmatrix} x_{G_0} \\ y_{G_0} \\ z_{G_0} \end{bmatrix}$$

At t=t $$\begin{bmatrix} x_{Lt} \\ y_{Lt} \\ z_{Lt} \end{bmatrix} = [M_B]_t \bullet \begin{bmatrix} x_{G_{L_t}} \\ y_{G_{L_t}} \\ z_{G_{L_t}} \end{bmatrix}$$

With reference to local system of trunk, where repositioning error between t=t and t=0,

Translation x-axis (Local): $x_{Local} = x_{L_t} - x_{L_0}$

Translation y-axis (Local): $y_{Local} = y_{L_t} - y_{L_0}$

Translation z-axis (Local): $y_{Local} = y_{L_t} - y_{L_0}$

x-axis (Local): "+" => Right sidegliding, "-" => Left sidegliding
y-axis (Local): "+" => Head protraction, "-" => Head retraction
z-axis (Local): "+" => Axial distraction, "-" => Axial compression

APPENDIX E

Analysis of Muscle Fatigue

The shift of electromyogram (EMG) frequency spectrum towards lower frequencies was used as an estimator of muscle fatigue (Oberg et al., 1990). The relative decrease in Mean Power Frequency (MPF) is significant if it exceed 8% of the initial MPF (MPF_0) as a result of muscle fatigue (Oberg et al., 1990) (Figure 1, 2). The subjective perception of muscular fatigue against time (i.e. Borg scale (0-10)) was included with case example of subject#77, the index reach 10 (i.e. maximum score) nearly every time after each fatiguing protocol which was marked as " ↓ "

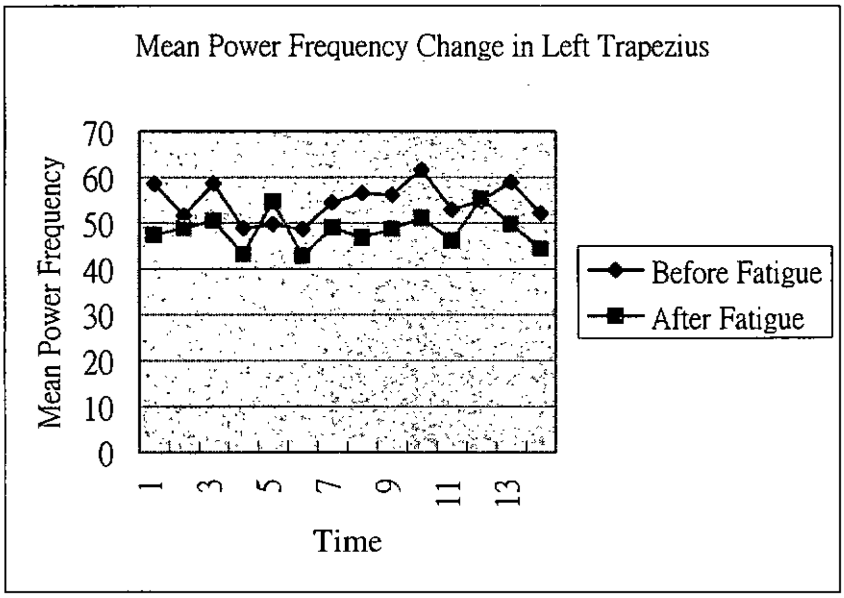

Figure.1 12.5% relative decrease in MPF value in relation to initial MPF (MPF_0) in Left trapezius after fatiguing protocol (Case example of subject#77)

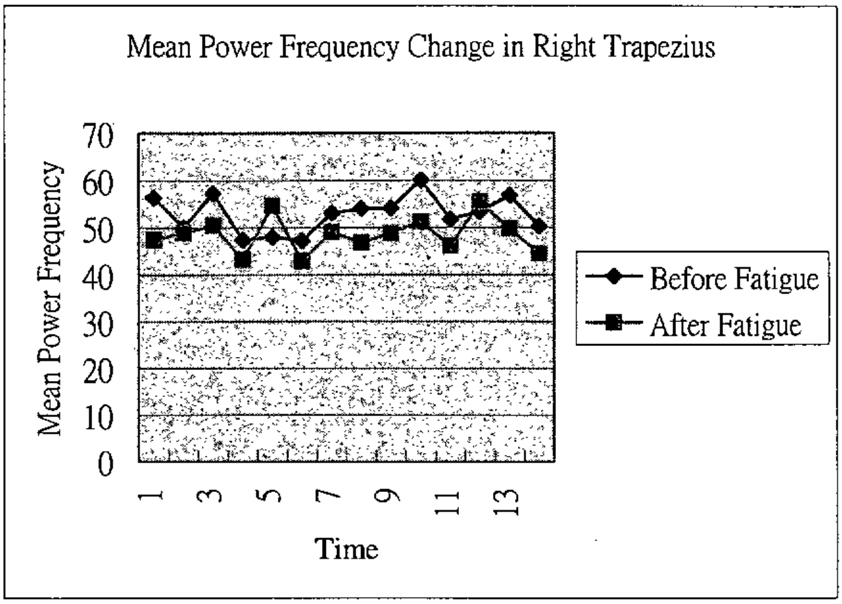

Figure.2 8.9% relative decrease in MPF value in relation to initial MPF (MPF_0) in Right Trapezius after fatiguing protocol (Case example of subject#77)

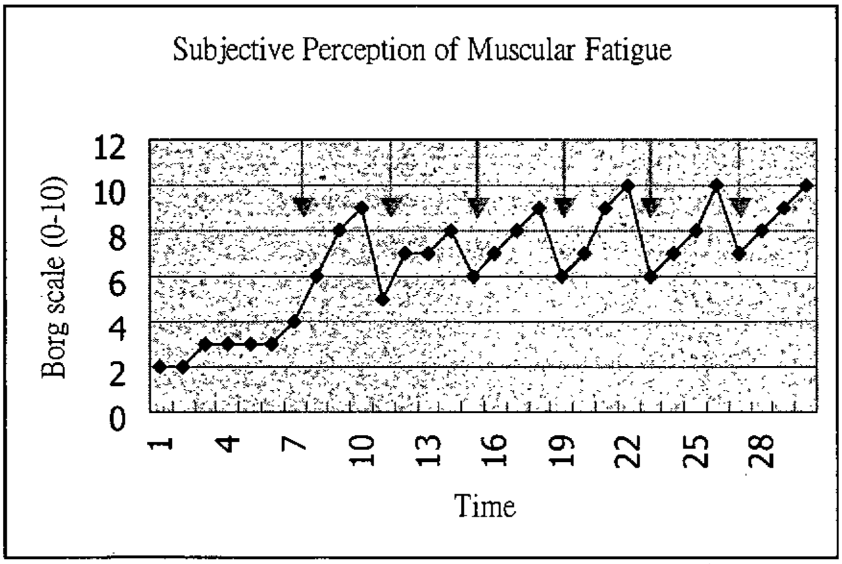

Figure.3 Subjective perception of muscular fatigue against time - Borg scale (0-10) (Case example of subject#77) ; note the start time of each fatiguing protocol was marked as " ↓ "

APPENDIX F: Statistical analysis Result

Flex(Project to global) (mean error)

(non-fatigued & eyes closed only)

Effect of TILTING

Estimates

Measure: MEASURE_1

TILTING	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	-.772	1.094	-3.061	1.518
2	2.027	.875	.196	3.858
3	1.878	.941	-.091	3.847

Pairwise Comparisons

Measure: MEASURE_1

(I) TILTING	(J) TILTING	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	-2.799*	.909	.019	-5.185	-.413
	3	-2.650	1.157	.101	-5.688	.388
2	1	2.799*	.909	.019	.413	5.185
	3	.149	1.005	1.000	-2.488	2.786
3	1	2.650	1.157	.101	-.388	5.688
	2	-.149	1.005	1.000	-2.786	2.488

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.345	4.733[a]	2.000	18.000	.022
Wilks' lambda	.655	4.733[a]	2.000	18.000	.022
Hotelling's trace	.526	4.733[a]	2.000	18.000	.022
Roy's largest roo	.526	4.733[a]	2.000	18.000	.022

Each F tests the multivariate effect of TILTING. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

TranslationX(Project to global) (mean error)

Effect of FATIGUE

Estimates[a]

Measure: MEASURE_1

FATIGUE	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	-.395	.446	-1.329	.538
2	.804	.596	-.442	2.051

a. Variable = TranslatX(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) FATIGUE	(J) FATIGUE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-1.200*	.572	.049	-2.396	-.003
2	1	1.200*	.572	.049	.003	2.396

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatX(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.188	4.403[a]	1.000	19.000	.049
Wilks' lambda	.812	4.403[a]	1.000	19.000	.049
Hotelling's trace	.232	4.403[a]	1.000	19.000	.049
Roy's largest roo	.232	4.403[a]	1.000	19.000	.049

Each F tests the multivariate effect of FATIGUE. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatX(Project to global)

TranslationY(Project to global) (mean error)

(non-fatigued only)

Effect of TILTING

Estimates

Measure: MEASURE_1

TILTING	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	-3.721	1.787	-7.462	.020
2	-1.733	1.739	-5.373	1.907
3	1.991	1.562	-1.278	5.260

Pairwise Comparisons

Measure: MEASURE_1

(I) TILTING	(J) TILTING	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	-1.988	.979	.170	-4.559	.583
	3	-5.712*	1.632	.007	-9.998	-1.427
2	1	1.988	.979	.170	-.583	4.559
	3	-3.724*	1.372	.041	-7.327	-.121
3	1	5.712*	1.632	.007	1.427	9.998
	2	3.724*	1.372	.041	.121	7.327

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.392	5.810[a]	2.000	18.000	.011
Wilks' lambda	.608	5.810[a]	2.000	18.000	.011
Hotelling's trace	.646	5.810[a]	2.000	18.000	.011
Roy's largest roo	.646	5.810[a]	2.000	18.000	.011

Each F tests the multivariate effect of TILTING. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

TranslationY(Project to global) (mean error)

(eyes closed only)

Effect of TILTING

Estimates

Measure: MEASURE_1

TILTING	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	-4.943	1.338	-7.743	-2.142
2	-2.426	1.561	-5.692	.841
3	.319	1.643	-3.119	3.758

Pairwise Comparisons

Measure: MEASURE_1

(I) TILTING	(J) TILTING	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-2.517	1.134	.116	-5.494	.460
	3	-5.262*	1.899	.037	-10.248	-.276
2	1	2.517	1.134	.116	-.460	5.494
	3	-2.745	1.710	.375	-7.233	1.743
3	1	5.262*	1.899	.037	.276	10.248
	2	2.745	1.710	.375	-1.743	7.233

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.317	4.178[a]	2.000	18.000	.032
Wilks' lambda	.683	4.178[a]	2.000	18.000	.032
Hotelling's trace	.464	4.178[a]	2.000	18.000	.032
Roy's largest roo	.464	4.178[a]	2.000	18.000	.032

Each F tests the multivariate effect of TILTING. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

TranslationY(Project to global) (mean error)

(eyes open only)

Effect of TILTING

Estimates

Measure: MEASURE_1

TILTING	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	-2.768	1.326	-5.543	.008
2	-1.601	1.447	-4.628	1.427
3	1.518	1.182	-.955	3.991

Pairwise Comparisons

Measure: MEASURE_1

(I) TILTING	(J) TILTING	Mean Difference (I-J)	Std. Error	Sig.^{a}	95% Confidence Interval for Difference^a	
					Lower Bound	Upper Bound
1	2	-1.167	1.105	.912	-4.067	1.733
	3	-4.286*	1.020	.001	-6.962	-1.609
2	1	1.167	1.105	.912	-1.733	4.067
	3	-3.119*	1.075	.028	-5.941	-.296
3	1	4.286*	1.020	.001	1.609	6.962
	2	3.119*	1.075	.028	.296	5.941

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.500	8.997^a	2.000	18.000	.002
Wilks' lambda	.500	8.997^a	2.000	18.000	.002
Hotelling's trace	1.000	8.997^a	2.000	18.000	.002
Roy's largest roo	1.000	8.997^a	2.000	18.000	.002

Each F tests the multivariate effect of TILTING. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

TranslationZ(Project to global) (mean error)

Effect of TILTING

Estimates[a]

Measure: MEASURE_1

TILTING	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.442	.538	.315	2.568
2	.527	.414	-.340	1.394
3	.245	.395	-.581	1.070

a. Variable = TranslatZ(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) TILTING	(J) TILTING	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.914*	.339	.043	.023	1.805
	3	1.197*	.448	.045	.022	2.372
2	1	-.914*	.339	.043	-1.805	-.023
	3	.283	.367	1.000	-.682	1.247
3	1	-1.197*	.448	.045	-2.372	-.022
	2	-.283	.367	1.000	-1.247	.682

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatZ(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.322	4.279[a]	2.000	18.000	.030
Wilks' lambda	.678	4.279[a]	2.000	18.000	.030
Hotelling's trace	.475	4.279[a]	2.000	18.000	.030
Roy's largest roo	.475	4.279[a]	2.000	18.000	.030

Each F tests the multivariate effect of TILTING. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatZ(Project to global)

TranslationX(Project to local) (mean error)

Effect of FATIGUE

Estimates[a]

Measure: MEASURE_1

FATIGUE	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	-.257	.354	-.998	.484
2	.875	.489	-.148	1.899

a. Variable = TranslatX(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) FATIGUE	(J) FATIGUE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	-1.132*	.442	.019	-2.058	-.207
2	1	1.132*	.442	.019	.207	2.058

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatX(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.257	6.562[a]	1.000	19.000	.019
Wilks' lambda	.743	6.562[a]	1.000	19.000	.019
Hotelling's trace	.345	6.562[a]	1.000	19.000	.019
Roy's largest roo	.345	6.562[a]	1.000	19.000	.019

Each F tests the multivariate effect of FATIGUE. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatX(Project to local)

TranslationY(Project to local) (mean error)

(Backback Tilted & eyes closed only)

Effect of FATIGUE

Estimates

Measure: MEASURE_1

FATIGUE	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	-4.146	1.827	-7.970	-.321
2	2.274	1.701	-1.286	5.835

Pairwise Comparisons

Measure: MEASURE_1

(I) FATIGUE	(J) FATIGUE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-6.420*	1.882	.003	-10.358	-2.482
2	1	6.420*	1.882	.003	2.482	10.358

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.380	11.642[a]	1.000	19.000	.003
Wilks' lambda	.620	11.642[a]	1.000	19.000	.003
Hotelling's trace	.613	11.642[a]	1.000	19.000	.003
Roy's largest roo	.613	11.642[a]	1.000	19.000	.003

Each F tests the multivariate effect of FATIGUE. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

TranslationZ(Project to local) (mean error)
(non-fatigued only)

Effect of VISION

Estimates

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	-.240	.392	-1.059	.580
2	.576	.350	-.157	1.309

Pairwise Comparisons

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.816*	.257	.005	-1.354	-.278
2	1	.816*	.257	.005	.278	1.354

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.346	10.063[a]	1.000	19.000	.005
Wilks' lambda	.654	10.063[a]	1.000	19.000	.005
Hotelling's trace	.530	10.063[a]	1.000	19.000	.005
Roy's largest roo	.530	10.063[a]	1.000	19.000	.005

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

TranslationZ(Project to local) (mean error)

(non-fatigued only)

Effect of VISION

Estimates

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	-.240	.392	-1.059	.580
2	.576	.350	-.157	1.309

Pairwise Comparisons

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.816*	.257	.005	-1.354	-.278
2	1	.816*	.257	.005	.278	1.354

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.346	10.063[a]	1.000	19.000	.005
Wilks' lambda	.654	10.063[a]	1.000	19.000	.005
Hotelling's trace	.530	10.063[a]	1.000	19.000	.005
Roy's largest roo	.530	10.063[a]	1.000	19.000	.005

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

Rot(Project to global) (absolute error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.504	.264	1.952	3.056
2	2.056	.274	1.483	2.629

a. Variable = Rot(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.448*	.175	.019	.082	.814
2	1	-.448*	.175	.019	-.814	-.082

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Rot(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.257	6.560[a]	1.000	19.000	.019
Wilks' lambda	.743	6.560[a]	1.000	19.000	.019
Hotelling's trace	.345	6.560[a]	1.000	19.000	.019
Roy's largest roo	.345	6.560[a]	1.000	19.000	.019

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Rot(Project to global)

Rot(Project to local) (absolute error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.340	.209	1.901	2.778
2	1.955	.208	1.519	2.392

a. Variable = Rot(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.384*	.170	.036	.028	.740
2	1	-.384*	.170	.036	-.740	-.028

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Rot(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.212	5.104[a]	1.000	19.000	.036
Wilks' lambda	.788	5.104[a]	1.000	19.000	.036
Hotelling's trace	.269	5.104[a]	1.000	19.000	.036
Roy's largest roo	.269	5.104[a]	1.000	19.000	.036

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Rot(Project to local)

TranslationY(Project to global) (absolute error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	7.766	.574	6.564	8.967
2	6.204	.616	4.914	7.494

a. Variable = TranslatY(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	1.562*	.453	.003	.614	2.509
2	1	-1.562*	.453	.003	-2.509	-.614

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatY(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.385	11.898[a]	1.000	19.000	.003
Wilks' lambda	.615	11.898[a]	1.000	19.000	.003
Hotelling's trace	.626	11.898[a]	1.000	19.000	.003
Roy's largest roo	.626	11.898[a]	1.000	19.000	.003

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatY(Project to global)

TranslationZ(Project to global) (absolute error)

Effect of TILTING

Estimates[a]

Measure: MEASURE_1

TILTING	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.966	.373	2.185	3.748
2	2.188	.292	1.577	2.799
3	2.534	.250	2.011	3.057

a. Variable = TranslatZ(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) TILTING	(J) TILTING	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.778*	.196	.002	.263	1.293
	3	.433	.360	.731	-.511	1.377
2	1	-.778*	.196	.002	-1.293	-.263
	3	-.346	.279	.690	-1.077	.386
3	1	-.433	.360	.731	-1.377	.511
	2	.346	.279	.690	-.386	1.077

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatZ(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.496	8.873[a]	2.000	18.000	.002
Wilks' lambda	.504	8.873[a]	2.000	18.000	.002
Hotelling's trace	.986	8.873[a]	2.000	18.000	.002
Roy's largest roo	.986	8.873[a]	2.000	18.000	.002

Each F tests the multivariate effect of TILTING. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatZ(Project to global)

TranslationY(Project to local) (absolute error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	7.059	.676	5.644	8.474
2	6.071	.746	4.510	7.631

a. Variable = TranslatY(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.989*	.408	.026	.134	1.843
2	1	-.989*	.408	.026	-1.843	-.134

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatY(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.236	5.864[a]	1.000	19.000	.026
Wilks' lambda	.764	5.864[a]	1.000	19.000	.026
Hotelling's trace	.309	5.864[a]	1.000	19.000	.026
Roy's largest roo	.309	5.864[a]	1.000	19.000	.026

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatY(Project to local)

TranslationZ(Project to local) (absolute error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.328	.235	1.836	2.820
2	2.061	.267	1.503	2.619

a. Variable = TranslatZ(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.267*	.111	.026	.035	.500
2	1	-.267*	.111	.026	-.500	-.035

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatZ(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.234	5.815[a]	1.000	19.000	.026
Wilks' lambda	.766	5.815[a]	1.000	19.000	.026
Hotelling's trace	.306	5.815[a]	1.000	19.000	.026
Roy's largest roo	.306	5.815[a]	1.000	19.000	.026

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatZ(Project to local)

Flex(Project to global) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.117	.138	1.827	2.406
2	1.875	.144	1.573	2.177

a. Variable = Flex(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.242*	.074	.004	.087	.397
2	1	-.242*	.074	.004	-.397	-.087

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Flex(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.360	10.686[a]	1.000	19.000	.004
Wilks' lambda	.640	10.686[a]	1.000	19.000	.004
Hotelling's trace	.562	10.686[a]	1.000	19.000	.004
Roy's largest roo	.562	10.686[a]	1.000	19.000	.004

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Flex(Project to global)

Sideflex(Project to global) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	1.048	.094	.852	1.244
2	.868	.068	.727	1.009

a. Variable = Sideflex(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	.180*	.058	.006	.059	.301
2	1	-.180*	.058	.006	-.301	-.059

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Sideflex(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.339	9.749[a]	1.000	19.000	.006
Wilks' lambda	.661	9.749[a]	1.000	19.000	.006
Hotelling's trace	.513	9.749[a]	1.000	19.000	.006
Roy's largest roo	.513	9.749[a]	1.000	19.000	.006

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Sideflex(Project to global)

Rot(Project to global) (variability error)

Effect of FATIGUE

Estimates[a]

Measure: MEASURE_1

FATIGUE	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	1.819	.231	1.335	2.302
2	1.600	.180	1.223	1.977

a. Variable = Rot(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) FATIGUE	(J) FATIGUE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	.219*	.076	.010	.059	.379
2	1	-.219*	.076	.010	-.379	-.059

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Rot(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.302	8.238[a]	1.000	19.000	.010
Wilks' lambda	.698	8.238[a]	1.000	19.000	.010
Hotelling's trace	.434	8.238[a]	1.000	19.000	.010
Roy's largest roo	.434	8.238[a]	1.000	19.000	.010

Each F tests the multivariate effect of FATIGUE. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Rot(Project to global)

Rot(Project to global) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.858	.178	1.486	2.230
2	1.561	.243	1.051	2.070

a. Variable = Rot(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.298*	.126	.029	.034	.562
2	1	-.298*	.126	.029	-.562	-.034

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Rot(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.227	5.567[a]	1.000	19.000	.029
Wilks' lambda	.773	5.567[a]	1.000	19.000	.029
Hotelling's trace	.293	5.567[a]	1.000	19.000	.029
Roy's largest roo	.293	5.567[a]	1.000	19.000	.029

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Rot(Project to global)

Flex(Project to local) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	2.119	.141	1.824	2.413
2	1.851	.139	1.560	2.143

a. Variable = Flex(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	.267*	.072	.001	.117	.417
2	1	-.267*	.072	.001	-.417	-.117

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Flex(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.422	13.898[a]	1.000	19.000	.001
Wilks' lambda	.578	13.898[a]	1.000	19.000	.001
Hotelling's trace	.731	13.898[a]	1.000	19.000	.001
Roy's largest roo	.731	13.898[a]	1.000	19.000	.001

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Flex(Project to local)

SideFlex(Project to local) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.049	.090	.860	1.237
2	.907	.091	.717	1.098

a. Variable = Sideflex(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.141*	.054	.017	.028	.255
2	1	-.141*	.054	.017	-.255	-.028

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Sideflex(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.263	6.777[a]	1.000	19.000	.017
Wilks' lambda	.737	6.777[a]	1.000	19.000	.017
Hotelling's trace	.357	6.777[a]	1.000	19.000	.017
Roy's largest roo	.357	6.777[a]	1.000	19.000	.017

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Sideflex(Project to local)

Rot(Project to local) (variability error)

Effect of FATIGUE

Estimates[a]

Measure: MEASURE_1

FATIGUE	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	1.688	.177	1.317	2.059
2	1.464	.129	1.193	1.734

a. Variable = Rot(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) FATIGUE	(J) FATIGUE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	2	.224*	.087	.019	.041	.407
2	1	-.224*	.087	.019	-.407	-.041

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Rot(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.257	6.584[a]	1.000	19.000	.019
Wilks' lambda	.743	6.584[a]	1.000	19.000	.019
Hotelling's trace	.347	6.584[a]	1.000	19.000	.019
Roy's largest roo	.347	6.584[a]	1.000	19.000	.019

Each F tests the multivariate effect of FATIGUE. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Rot(Project to local)

Rot(Project to local) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.771	.139	1.480	2.061
2	1.381	.170	1.026	1.736

a. Variable = Rot(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.390*	.086	.000	.210	.570
2	1	-.390*	.086	.000	-.570	-.210

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = Rot(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.520	20.570[a]	1.000	19.000	.000
Wilks' lambda	.480	20.570[a]	1.000	19.000	.000
Hotelling's trace	1.083	20.570[a]	1.000	19.000	.000
Roy's largest roo	1.083	20.570[a]	1.000	19.000	.000

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = Rot(Project to local)

TranslationX(Project to global) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	2.110	.172	1.750	2.471
2	1.788	.183	1.404	2.172

a. Variable = TranslatX(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.322*	.098	.004	.118	.527
2	1	-.322*	.098	.004	-.527	-.118

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatX(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.364	10.884[a]	1.000	19.000	.004
Wilks' lambda	.636	10.884[a]	1.000	19.000	.004
Hotelling's trace	.573	10.884[a]	1.000	19.000	.004
Roy's largest roo	.573	10.884[a]	1.000	19.000	.004

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatX(Project to global)

TranslationY(Project to global) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	4.240	.338	3.533	4.947
2	3.424	.284	2.831	4.018

a. Variable = TranslatY(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.815*	.270	.007	.250	1.381
2	1	-.815*	.270	.007	-1.381	-.250

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatY(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.324	9.099[a]	1.000	19.000	.007
Wilks' lambda	.676	9.099[a]	1.000	19.000	.007
Hotelling's trace	.479	9.099[a]	1.000	19.000	.007
Roy's largest roo	.479	9.099[a]	1.000	19.000	.007

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatY(Project to global)

TranslationZ(Project to global)

(variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.483	.138	1.194	1.771
2	1.232	.131	.957	1.506

a. Variable = TranslatZ(Project to global)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.251*	.077	.004	.089	.413
2	1	-.251*	.077	.004	-.413	-.089

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatZ(Project to global)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.357	10.531[a]	1.000	19.000	.004
Wilks' lambda	.643	10.531[a]	1.000	19.000	.004
Hotelling's trace	.554	10.531[a]	1.000	19.000	.004
Roy's largest roo	.554	10.531[a]	1.000	19.000	.004

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatZ(Project to global)

TranslationX(Project to local) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.937	.146	1.632	2.242
2	1.635	.138	1.346	1.924

a. Variable = TranslatX(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.303*	.065	.000	.166	.439
2	1	-.303*	.065	.000	-.439	-.166

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatX(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.532	21.628[a]	1.000	19.000	.000
Wilks' lambda	.468	21.628[a]	1.000	19.000	.000
Hotelling's trace	1.138	21.628[a]	1.000	19.000	.000
Roy's largest roo	1.138	21.628[a]	1.000	19.000	.000

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatX(Project to local)

TranslationY(Project to local) (variability error)

Effect of VISION

Estimates[a]

Measure: MEASURE_1

VISION	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	4.129	.389	3.314	4.943
2	3.577	.360	2.822	4.331

a. Variable = TranslatY(Project to local)

Pairwise Comparisons[b]

Measure: MEASURE_1

(I) VISION	(J) VISION	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.552*	.201	.013	.132	.972
2	1	-.552*	.201	.013	-.972	-.132

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

b. Variable = TranslatY(Project to local)

Multivariate Tests[b]

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.285	7.566[a]	1.000	19.000	.013
Wilks' lambda	.715	7.566[a]	1.000	19.000	.013
Hotelling's trace	.398	7.566[a]	1.000	19.000	.013
Roy's largest roo	.398	7.566[a]	1.000	19.000	.013

Each F tests the multivariate effect of VISION. These tests are based on the linearly pairwise comparisons among the estimated marginal means.

a. Exact statistic

b. Variable = TranslatY(Project to local)

TranslationZ(Project to local) (variability error)
(eyes closed only)

Effect of FATIGUE

Estimates

Measure: MEASURE_1

FATIGUE	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	1.588	.236	1.094	2.083
2	1.118	.142	.822	1.415

Pairwise Comparisons

Measure: MEASURE_1

(I) FATIGUE	(J) FATIGUE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.470*	.184	.019	.085	.855
2	1	-.470*	.184	.019	-.855	-.085

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Multivariate Tests

	Value	F	Hypothesis df	Error df	Sig.
Pillai's trace	.256	6.544[a]	1.000	19.000	.019
Wilks' lambda	.744	6.544[a]	1.000	19.000	.019
Hotelling's trace	.344	6.544[a]	1.000	19.000	.019
Roy's largest roo	.344	6.544[a]	1.000	19.000	.019

Each F tests the multivariate effect of FATIGUE. These tests are based on the linearl pairwise comparisons among the estimated marginal means.

a. Exact statistic

APPENDIX G

Calibration of motion analysis system

The Vicon motion analysis system was calibrated using custom-made calibration device described in previous study (Chow, 1994) to determine the experimental errors associated with the current setting of the motion analysis system and the calculation method involved. The calibration device consisted of two parts which can be set at different relative rotations to each other in three axes of rotation. Markers were attached to the device in the same fashion as the testing procedure in the current experiment. The known degree of rotation was applied to the upper portion of the device relative to the lower portion of the device. The position of the markers was captured by the Vicon motion analysis system for two seconds, and then the relative position of the upper part to the lower part of the calibration device was calculated using the same method as in appendix D. Three trials were captured for each of the calibration angles used, and the results were shown in the following table. It was found that the standard deviation of the repeated measurements at each calibration angle is less than 0.05°. Besides, root mean square difference between the absolute values of the calibration angle and the calculated angle was 1.14° averaged over all of the measured angles.

Calibration angle (degrees)	Calculated angle			Mean	SD
	1 st trial	2 nd trial	3 rd trial		
1	1.78	1.78	1.78	1.78	0.00
2	2.97	2.98	2.97	2.97	0.00
3	4.08	4.09	4.09	4.09	0.00
4	5.11	5.11	5.11	5.11	0.00
5	6.12	6.13	6.12	6.12	0.00
10	11.14	11.14	11.14	11.14	0.00
20	21.14	21.13	21.14	21.14	0.00
30	31.08	31.08	31.08	31.08	0.00
40	40.98	40.98	40.98	40.98	0.00
50	51.01	51.02	51.02	51.02	0.01
60	61.29	61.29	61.29	61.29	0.00
70	71.47	71.47	71.47	71.47	0.00
80	82.03	81.17	81.60	81.60	0.43

Table 1. The calculated angles obtained with each calibration angles