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Comparison of a Single-Camera System with the 3D Vicon System on the Upper Limb Coordination and Trunk Compensation in Stroke Survivors

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Signed: Georgia Tarfali

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Abstract

Stroke is one of the major causes of physical disability in adults worldwide. Upper limb (UL) is commonly impaired after stroke, with most of patients experiencing acute or chronic hemiparesis. New rehabilitation treatments for more effective recovery of the hemiparetic upper limb function have triggered the interest of clinical researchers. Impairment and disability in clinical settings is generally assessed by ordinal scales such as the Fugl-Meyer Assessment, Action Research Arm Test etc. but they provide low sensitivity and reliability. Within recent years, scientific researchers have focused increasing attention on measuring upper limb kinematics in order to obtain an objective evaluation of the effectiveness of rehabilitation treatment following stroke. Three- dimensional analysis provides quantitative assessment of upper limb motion however, it is far to be commonly diffused in clinical practice since it is quite expensive and need high-structured laboratories. The purpose of this study is to compare a cheap, portable single-camera system to the 3D Vicon system on the assessment of upper limb motion in stroke patients.

Five healthy participant and five stroke patients took part in this study. Participants were asked to perform a reach to grasp movement in a series of five trials. A single- camera system (210 Hz) and a 12-camera Vicon 3D motion analysis system (100 Hz) were employed to simultaneously capture the reaching task. Upper limb coordination (% percentage) and forward trunk tilt (degrees) were the parameters under investigation. Statistical analyses show an overall good agreement between the measurement systems for both the parameters. However, it appears that the 2D single camera is more accurate in measuring trunk tilt than upper limb coordination in stroke patients.

This study introduces the use of a cheap single camera system in clinical settings for the assessment of upper limb motion in stroke patients enabling future studies to establish it as evaluation outcome measure in research field.

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List of Acronyms

***Abbreviation*:**	***Definition:***
UL	Upper Limb
UE	Upper Extremity
ADL	Central Nervous System
CNS	Activities of Daily Living
3D	Three dimension
2D	Two dimension
ROM	Range Of Motion
FMA	Fugl- Meyer Assessment
ARAT	Action Research Arm test
WMFT	Wolf Motor Function Test
BBT	Block and Box Test
ICC	Intra-class Correlation Coefficient
S.D	Standard Deviation
C.I	Confidence Interval

1 Introduction

1.1 Background and aims

Stroke is one of the major causes of physical disability in adults worldwide (Gillard, 2013). Approximately 152,000 strokes per year are observed in the UK (Townsend et al., 2012). Studies reveal that the 80% of patients experience acute hemiparesis and the 40% experience chronic hemiparesis. Upper limb's (UL) movement is commonly impaired after central lesions such as stroke (Warllow, 2008). According to Twitchell (1951), motor recovery after stroke proceeds through a stepwise sequence. Both upper and lower limbs undergo an initial flaccid paralysis with the absence of reflexes. The hypotonic phase is followed by overactive reflexes, muscle tone increase and development of spasticity. Subsequently, a voluntary stereotype movement is achieved, known as ''synergy''; after a period, movements can be even achieved out of synergy. Finally, the muscle tone and the reflexes may become normalized. Nevertheless, recovery does not mean that has to pass along all these stages; the rate and the degree of recovery is entirely individual matter, leaving always residual impairment (Twichell, 1951). Hence, the hemiparetic upper limb remains an obstacle to re-establishment of autonomy, decreasing the quality of life of patients and of their families (Kamper et al., 2002).

Normal upper limb function, including reach to grasp movement, is the basis for the activities of daily livings (ADL) such as feeding, grooming, dressing and writing (Haggard et al, 1998). Moreover, upper limb function plays crucial role in motor skills such as walking and maintenance of static and dynamic body balance (Shumway-Cook and Woollacott, 2007). Studies suggest that during bipedal locomotion there is a neuronal coupling between the muscles of arms and legs, making the normal upper limb function essential for gait (Dietz et al., 2001). In addition, upper limp swinging during human gait contributes to the neutralization of lower's body angular moments (Umberger, 2008). Consequently, the importance of normal upper limb function in the individual's quality of life has turned the interest of research field on studying the optimum upper limb recovery following stroke.

Restoring upper limb function is main concern in post stroke rehabilitation. Currently, new rehabilitation techniques have been introduced to improve upper limb function. Constraint-induced movement therapy is an intensive rehabilitation approach; the patient has to wear a restrained device in the non-affective upper limb while he is forced to use the impaired arm to accomplish several tasks of different complexity and difficulty level (Oujamaa, 2009). Task- specific and repetitive exercises are essentials parameters in motivating new synapsis in CNS, thus improving the post stroke motor weakness (O' Dell et al., 2009). New technologies including feedback devices, virtual reality and robot- aided therapy have been developed for stimulating the brain tissue to recover (Kalra, 2009). However, the most appropriate rehabilitation approach remains unknown and may vary according to factors such as severity, location and stage of the disease (Oujamaa et al., 2009). Thereby, it is not known whether the lack of evidence for comprehensive functional improvement following stroke is due to poor treatment efficacy or to less accurate and precise outcome measures.

There is no doubt that a key factor in understanding which interventions are most effective is the outcome measures used. Impairment and disability is generally assessed by ordinal scales such as the Fugl-Meyer Assessment, ARAT etc., but they do not provide high sensitivity and reliability (Murphy at al., 2011). These scales identify the performance or/ and the impairment level of upper extremity (Lang et al, 2013). Quantifying upper limb dysfunction is complicated procedure since upper extremity is multi-joint structure with a variability of possible movements. Optical motion capture systems provide quantitative assessment of upper limb motion and they have been adopted for motion analysis in stroke patients. The comparison of upper limb's pathological intersegment coordination with the normal trajectories or the assessment of the compensatory movements could be well described by 3D analysis systems (Van Andel et al, 2008). However, 3-D video motion analysis system has limited utility in clinical practice since it is expensive, need high-structured laboratories and trained personnel (Nowak, 2008).

The need of a new assessment method of the hemiparetic upper which could combine the quantitative outcomes of three dimensional analysis while being ease and affordable in use, is apparently obvious. Two dimensional (2D) analysis might include these characteristic, therefore there is lack of validity studies for the employment of 2D video in upper limb assessment. The purpose of this study was to compare the kinematic data gathered by an inexpensive, portable single camera motion analysis system with those obtained by the ʹʹgold standardʹʹ in three dimension motion analysis, Vicon system. In particular, variables as the upper limb intersegment coordination and the trunk compensation in stoke patient during reaching movement were measured. The aim of the study, hence, was to identify the agreement between the data of the 2D and 3D motion analysis systems. Therefore, we hypothesize that the proposed system may be effective on capturing upper extremity and trunk movements in stroke patients.

1.2 Layout of thesis

Since the upper limb is associated with both the fine and gross motor skills, the principles of reaching control are described in the beginning of the second chapter. The next chapter analyzes the UL’s abnormal patterns following a stroke. Then, the main functional scales and human motion capture systems being widely used in research and rehabilitation field for the evaluation of UL impairment are listed. Finally, the theory is completed with the available literature review regarding the comparison between the 3D and 2D motion analysis systems on capturing human motion. Methodology presents information about the participants and the protocol of the study. Results show the findings obtained from the analysis of video and Vicon system data. The thesis is finishing with a discussion, conclusions and future recommendations for similar studies with bigger sample size.

2 Literature review

2.1 Biomechanics of Normal Reaching

The movements of proximal and distal segments of the upper limb are spatiotemporally coordinated during reach and grasp movements. These movements involve two different visuo- motor channels with a temporal coupling between them. The first component, hand transport, is responsible to move the hand towards to the target using information regarding the position of the object. The second part, named hand aperture, uses stimulus of the object's characteristic (size, weight, etc.) and it prepares the hand for the grasping. Whereas those two channels use different type of information, they are synchronized in manner that both of them coexist during the reach to grasp movement (Haggard et al, 1998). However, arguments exist regarding the coordination between the two components. The suggestion of the temporal mechanism contradicts with the theory of the higher- order motor control (Wang et al, 1998).

Movements involving reaching tasks are very useful for the determination of coordination. In particular, muscles acting at the shoulder and at the elbow must be controlled in order to move the hand. The neuromuscular control in this task also requires the coordination of the muscles responsible for the postural stabilization. Joint torque and inertia force of each joint are responsible for the acceleration during a reach to grasp movement. In particular, there is a coupling between the rotational inertias of upper limb's joints and the movements of upper limb's segments (arm, forearm, hand). The total joint torque is derived from the muscle activity, the joint viscoelasticity and the gravitational and external applied forces (Ventura et al., 1999).

Reaching to grasp movement is also accompanied by trunk movement. That is, reaching involves movement of the arm or of the trunk or a combination of both. Saling et al (1996) found that the trunk and arm movements have an independent control by the central nervous system (CNS). Wang et al. (1998) in their study hypothesized that hand kinematics are not affected by the participation of arm or trunk motion, during a reach to grasp task. They collected kinematic data of ten healthy college students' upper limbs during a reach to grasp movement, in different combination of trunk-arm motion. They concluded that spatiotemporal kinematics in grasp component remained the same despite the alterations in the parameters related to the transport component. These findings indicate that the two components of grasp to reach movement are governed by different motor synergies. Furthermore, the motion of arm and trunk are coordinated to keep the endpoint motion stable (Wang et.al. 1998, Stelmach et al., 1998). Normally, in healthy people, if the target is placed within the arm's length, the reaching movement involves the shoulder, elbow and wrist. However, reaching to a target beyond arm's length includes supplementary movement of the trunk and hip. Thereafter, based on the coordination of these joints, the hand can reach accurately the chosen position (McCrea et al, 2012). Cirstea et al observed that most healthy people initiate a pointing movement by flexing their elbow and their shoulder to raise the arm and in sequence they move it towards to the target with horizontal adduction in the shoulder and extension in the elbow. People accomplish this task with a minimal amount of movement in the trunk (Cirstea et al, 2000).

The upper limb consists of segments moved about seven degrees of freedom (DOF) in total. Particularly, there are three DOF in shoulder (flexion-extension, abduction-adduction, internal-external rotations), one DOF in elbow (flexion-extension), one DOF in forearm (pronation-supination), two DOF in wrist (flexion-extension and ulnar-radial deviation) plus the movements of shoulder-scapula complex (elevation/depression, protraction/ retraction) (Magee, 2008). Nevertheless, this abundance of joint motion does not greatly alter the typical motion synergy during a reach to grasp movement, in healthy population. The joint motion is almost identical for a specific start point, end point and hand trajectory in reaching tasks In the CNS, spatial information is converted to motor patterns at the shoulder and elbow in order to move the hand in the space. Analytically, the sensory signals are transformed first into hand trajectories and in sequence into joint trajectories. At the end they are converted into patterns of the upper limb's muscles groups. Furthermore, this natural excess of joint motion not only provides the CNS with a variety of different paths for the accomplishment of the upper limb movement, but it also affords the adaption of alternatives paths or compensative movements after a central or peripheral injury (Yang et. al, 2002).

Reach to grasp tasks are controlled by CNS using feed forward and feedback strategies. Feed forward control is referred in the first phase of reaching and it is responsible for the pre-programmed trajectories of the hand (Komura et al., 1997; Steenbergen et al., 2000). In this phase sensory information is used to anticipate the disturbances and program the activation of the appropriate muscles. Muscles activities and torques are a priori sufficient to cope with the interaction torques before the feedback control strategy is available. The importance of this anticipation can be further proved by alterations in hand paths and kinematics that happen when muscle torque and interaction torque are not well matched. It is suggested that the CNS take under consideration the predictions about the interaction torques in order to select the appropriate muscle activation or/and muscle torque (Galloway et al., 2001). In the next phase of reaching, the feedback phase controls the direction and the velocity of the arm through the space. During this phase information from the receptors of muscles, joints and others soft tissue are collected and directed towards CNS. Experience and practise contribute to learning new strategies for elimination and correction of the disturbances derived from external forces thereby controlling the voluntary movements (Mccrea et al, 2012).

In healthy populations, the velocity profile of a multijoint reaching is depicted as a smoothly bell shaped curve (Cirstea et al., 2000). The peak velocity is occurring in the middle of the path from the onset to the end of the movement. However, both the bell shaped velocity and the time when the peak value is observed could be altered depending on the accuracy requirements. In particular, high demands of accuracy results in skewed curves while the peak velocity occurs earlier in the task. Conversely, in high speed movements the peak velocity is noted in a later moment. Fitts' Law describes the relationship between the accuracy and the speed of reaching movement, indicating that their relationship is inversely proportional (Fitts, 1954).

The complex process of CNS on upper limb control is clearly demonstrated. As simple as it looks, a reach to grasp task requires the collaboration of all the components in order to be achieved a smooth and coordinated movement. Any dysfunction in the elements which control the upper limb movement could cause impairment. The following chapter focuses on describing problems in reaching tasks after a CNS lesion, in particular in stoke patients.

3 Biomechanics of Reaching in Stroke Survivors

Stroke patients’ disturbances of voluntary upper extremity motion can be attributed to weakness, abnormal co- activation of agonist-antagonist muscles and hypertonia (Beer et al., 2000). As mentioned in chapter two, reach and grasp are controlled by a different mechanism, which means that a deficit can occur independently in these two components. However, in neurological patients both reach and grasp are affected, resulting on dysfunction in UL motion. In contrast to straight and smoothly reaching trajectories performed by healthy people, movement trajectories in stroke patients are characterized by loss of coordinated coupling between synergistic muscles and joints. Coordination deficit affects the timing and trajectory of movements (Shumway-Cook and Woollacott, 2007). Clinically, stroke patients develop stereotypic movement patterns which involve a tight coupling motion at adjacent joints; this phenomenon is also called ‘’flexor and extensor limb synergies ‘’. In particular, there is a tight relationship between the muscles torques of shoulder and elbow joint (Brunnstrom, 1970). Atypical movement patterns causing difficulties in selective movements, are often observed in stoke patients. The patterns called ‘’synergies’’ have been defined as *‘’fixed patterns movement involving an entire extremity, with an inability to isolate movements outside of the synergy pattern’’* (Twichell, 1951). Therefore, the stereotypic movements of stroke patients have been described in terms of trajectory, velocity, accuracy and interjoint coordination (Kirstey et al., 2000).

Van Vliet et al. (2007) studied the UL’s kinematics in stroke patient and healthy subjects, and found that reaching movement was slower in stroke patients performing a longer deceleration phase. In addition, the temporal coordination between the two components of the movement was not coupled. Beer et al. (2000) also studied the deficit in coordination of multijoint UL’s movements in stroke patients with chronic hemiparesis. They observed a systematic misdirection in the onset of reach to grasp movement of the hemipretic UL in stroke survivors. Kinetics analysis showed that the misdirection was connecting with the abnormal spatial coordination of the muscle torques of the elbow.

Cirstea at al. (2000), studied upper limp movement patterns and compensation strategies for reaching following CNS lesion. They compared pointing movements between 9 stroke patients and 9 healthy subjects and they found that the main characteristics of arm trajectories in stoke patient were the segmentation and the dispersion. Moreover, slower movements which were characterized by decreased accuracy and coordination were also observed in stoke patients. Both shoulder-elbow coordination and active range of motion (ROM) were altered significantly compared with healthy individuals. Furthermore, it was observed that stroke subject tilted forward their trunk in order to compensate the deficit of the decreased ROM. The study concluded that there were a relationship between the use of trunk compensatory strategies and the degree of motor impairment. Similar results were found earlier by Levin at al. (1996) studying the relationship between functional limitations and impairments in hemiparetic upper limb. 10 stoke patients and 6 control subjects performed a pointing movement while the target was placed in four different distances and sides away from each subject. The results indicate that for all hemiparetic participants the movement was longer in duration, slower in velocity and with disruption in interjoint coordination. However, they concluded that the disruption in coordination was not strictly correlated only with the pathological synergies movement neither with the presence of spasticity. They suggested that despite the location of the lesion, the CNS may not be able to control optimally the coordination of upper limb.

The temporal coordination (TC) between shoulder and elbow during reaching movements in patients with left-sided cerebrovascular accident has been studied by Cirstea et al (2003). Three dimensional analysis has shown that, in mid –reach phase, patients were not able to coordinate elbow flexion with shoulder horizontal adduction. In end-reach phase all patients struggled to coordinate elbow extension with shoulder horizontal adduction while only patients with severe impairment had deficit in the accomplishment of elbow extension (Cirstea et. al, 2003). While Cirstea et al studied the coordination of upper limb joint during reaching movement Zackowski et al. (2004) were involved with the deficit in individuation during reaching in stroke patients. They evaluated both reaching up and reaching out movements; each one required different combination of shoulder-elbow movements. In addition, they measured the capacity of stoke patients to perform individual movement in shoulder, elbow and wrist. The results indicated that reaching out which requires flexion at the shoulder and extension at the elbow was worst in stoke patient compared to reaching up. This study also highlights that the abnormal individuation is the primary problem affecting the upper limb in people with chronic hemiparesis. McCrea et al. (2005), in contrast, argued that insufficient muscle strength is the cause for abnormal trajectories in the forward reaching tasks. Hence, other muscles had to recruit for the task accomplishment leading in upper limb segmentation. Many researchers support that spasticity is the primary cause for the impairment in hemiparetic upper limb (Bobath 1978;Davies, 1985). However, the extent to which the tone disorders affect the function of upper limb following a brain lesion is still unknown.

In all these studies, clinicians and researches used definition to describe the deficit or the loss of joint coordination in reaching tasks. ''Synergy'' is used as the abnormal patterns in chronic hemiparesis; other employ this terms to describe the normal interjoint coupling thereby the impairment in reaching is characterized as decrease in normal synergies. Also, different studies use different evaluation tools for the outcome measurements. 3D, 2D and ordinals scales were used for the description of the quality of movement during the performance of reach to grasp tasks. In the next chapter, therefore, we will describe the effectiveness of the currently used tools for the evaluation of the upper limb function.

4 Upper Limb Assessment

Measurement of upper limb's recovery after stroke is crucial for the determination of the level of disability and the planning of the appropriate rehabilitation program by the clinicians. Moreover, in research field an accurate and reliable evaluation tool tend to be the key element for valid results in studies involved patients recruitment. In fact, recent clinical trials failed due to the inappropriateness of the chosen outcome measure rather than to the failure of the method or the mean under investigation (Dunkan et al., 2000). The sensitivity of the evaluation mean is essential for highlighting even small changes. In addition, based on the individualization of upper limb recovery following stroke, the need for the evaluation and measurement of the impairment level is in great demand. Quantitative and qualitative assessments of hemiparetic upper limb motion are becoming increasingly important for testing the efficacy of a new or under investigation treatment protocol. Therefore, this chapter is dedicated to the description of the most widely used outcome measurements of upper limb function, including scales and motion capture systems.

4.1 Fugl-Meyer Assessment

Fugl- Meyer Assessment (FMA) is a well-established instrument for assessing the recovery in hemiplegic patient following stroke. It has been characterized as one of the most comprehensive evaluation scale of motor impairment and it is strongly recommended for both clinical and research use. It was developed based on Twitchell's (Twitchell, 1951) and Brunnstrom's (Brunnstrom, 1957) concepts of the stages of motor recovery in stroke survivors. The FM scale has 226 items and assess five domains: motor function, sensory function, balance, joint ROM and pain. Multiple items are included in each domain and each item can be scored on a 3 point ordinary scale (Table 4.1). In particular, the upper limb motor domain includes measurements of movement, coordination and reflexes of shoulder, elbow, forearm, wrist and hand. The range of motor score is between 0 and 100 points representing the hemiplegia and normal motor performance, respectively. The maximum score for the upper limb is 66 while for the lower limb 34 (100 in total). Furthermore, the maximum score for sensation is 24 points, 44 point for joint pain and 44 points for joint ROM as well. FM's scale administration time is approximately 30 min and it is best manipulated by a trained physical therapist.

Table 4-1: 3-point ordinal scale of Fugl-Meyer Assessment (Fugl- Meyer et al., 1971)

0	*Cannot perform*
1	*Performs partially*
2	*Performs fully*

4.1.1 Reliability

Based on the available studies, FMA is recommended as a valid clinical and research tool for upper limb evaluation. Fugl-Meyer et al. (1971) characterized their scale ''reliable'' due to the fixed and rigid procedure of the scale and the little chance of error. Duncan et al (1983) tested the intrarater and interrater reliability of FMA scale assessing 19 chronic stroke patients. They found high intrarater Pearson correlation coefficient (ICC) both for the total score (0.98-0.99) and for the upper limb motor score (0.995-0.996). Sensation, balance, joint range of motion and pain had high subscores as well ($P<0.001$ for all). They also studied the interrater reliability among 4 physiotherapist; the results highlighted that FMA scale has high interrater reliability for the motor performance of upper extremity (0.98-0.995). Furthermore, in the study of Sanford et al. (1993) 12 stroke patients were evaluated by 3 expert physical therapists, using the FMA scale, six months post-stroke. The results indicated high reliability while upper limb motor score showed the highest ICC values (0.97). Despite that both studies have shown significant good results for FMA reliability, slight concerns may exist due to the small number of the participant which limits the result's generalization. Also, the results are intended to stroke patients without any separation between moderate, mild and severe hemiplegia. It is anticipated, though, that individuals with severe impairment would show good interrater results because of their lower scores (almost ''0''). Hence, studies about the reliability of this scale should categorize the patients according to the severity of their impairment. In extension of the assessment of FMA reliability, a study for the assessment of hemiparetic upper limb function was conducted at 2005 in three different European Countries (Germany, UK, Italy). The researchers investigated the reliability of FMA, Action Research Arm Test (ARAT) and Box and Block tests (BBT) and they found high inter-rater reliability for all of the three tests. Additionally, test-retest reliability was found high thereby revealing a high degree of reproducibility (Platz et al., 2005).

4.1.2 Validity

DeWeerdt et al. (1985), compared the upper limb motor scores in FMA to the ARAT, assessing 53 patients at 2 and 8 weeks post stroke. The analysis of the results showed high correlation between the FMA's scale impairment scores and the clinically meaningful function of the arm. Despite the fact that the number of participants was good enough for the validation, the limitation of this study was in connection with the early of post stroke phase. Since recovery may proceed up to one year following stroke (Fugl-Meyer, 1975), it would be important to prove the validity even in subsequent phases of the motor recovery. Hence, FMA scale may have a ceiling effect in patients with improved upper limb motor function.

4.1.3 Sensitivity, Responsiveness

FMA scale appears to show sensitivity and responsiveness in the motor domain of the upper limb regarding the gross hand function. However, a remarkable omission is noted on the assessment of fine hand function, including finger extension, speed and dexterity. Good motor recovery of distal hand movements is underrepresented thereby patients with improved hand function cannot increase their score (ceiling effect). Moreover, motor domain does not assess any deficit of the trunk muscles (Gladstone, 2002).

Recently, researches demonstrated that FMA scale is sensitive in clinical changes in upper limb function. However, it showed low sensitivity on detection chances in grasping ability. Innovatively, the subject of this study was the estimation of the clinical importance difference (CID) of the FMA scale in 134 stroke patient with mild to moderate hemiplegia. The range of values for CID was found 4.25-7.25 points meaning that scores between these values are representative of clinical important changes. Nevertheless, these results are valid only for patients with similar level of disability with those participating on this study (Page et al., 2012).

4.1.4 Appropriateness, feasibility

The FMA scale has been characterized as feasible and appropriate assessment scale for the function of upper limb in stroke patients. The assessment does not require special equipment and the instructions to patients are easy and straightforward. FMA employs an easy scoring system; however, this scale is simple and valid only if it is administrated by a trained physical therapist. Also, FMA scale is time consuming procedure, especially when it is applied in less severe hemiparetic upper limbs. Therefore, this fact may be considered as an important limitation in clinical trials where a vast number of participants are recruited.

4.2 ARAT

Action Research Arm test (ARAT) is an assessment tool for the upper limb function including coordination, dexterity and ADL. It is an outcome measure of activity, thereby identifying the disability level of upper limb following stroke using observational methods (Steenberger et al., 2000). The ARAT is a 19-item measure divided into 4 sub-tests; grasp, grip, pinch and gross arm movement are included. Each item's performance is assessed using a 4-point ordinal scale (table 4.2). The test material includes a wooden box containing objects and blocks of different sizes. The box is placed in the table in front of the patient. During the test the ability of grasping, moving and realizing different sized, weighted and shaped objects are assessed. Further, gross movements such as place hand in the mouth, in the top or behind the head are tested (Van der Lee et al, 2001).

Table 4-2: 4- point ordinal scale of ARAT (Van der Lee et al, 2001)

3	Performs test normally
2	Completes test, but takes abnormally long or has great difficulty
1	Performs test partially
0	Can perform no part of test

According to Lyle's rule (Lyle, 1981), if patient achieves a maximum score on the first and most difficult item then he will receive a maximum score of '*3*' credits in the rest sub-items, as well. Hence, the second item is assessed only if the patient achieves less than '*3*' in the first item. Furthermore, in case that patient scores '*0*' in the second item, it is assumed that he is credited with '*0*' either in the remainder of items, since the second is the easiest one. Therefore, the maximum score for ARAT is 57 points. The administration time of the test is approximately 10 minutes while the total temporal length is estimated between 6 to 30 minutes, depending on the patient's severity of disability hence the number of items need to perform (Lyle, 1981).

Recently, Yozbatiran et al. (2008) suggested a standardized approach for assigning ARAT scores. They introduced a manual for scoring in order minimizing the variability coming from human's administration skills. As the majority of motor assessments, ARAT relies on the physician ability to transform the observed movements into a score. In ARAT there is a lower agreement of the scores between observers than within an observer (Nijland et al., 2010). For instance, in case that the patient *''can complete the test but takes abnormally long or has great difficulty''* he receives a score of 2; the statements *''abnormally long''* or *''great difficulty''* are not clearly defined. Therefore, Yozbatiran et al. (2008) presented a valid and reliable manual which defines, in more details, some operational definitions and scoring instructions. They included details in connection with the time in which a performance is defined as normal, the position of trunk and extremities as well as characteristics of the testing objects.

4.2.1 Reliability

ARAT has been characterized with good clinimetric properties (Van de Lee et al., 2001; Wolf et al., 2001; Yozbatiran et al, 2008; Lin et al., 2009). Nijland et al. (2010) compared the ARAT to the Wolf Motor Function Test (WMFT) on evaluation of upper limb motor function in forty stroke patients. Results indicated high intraclass correlation coefficient for inter-rater and intra-rater reliability (0.92 and 0.97, respectively). In a similar vein, Van der Lee and his colleagues (2001) found high value of ICC 0.98 for intra-rater reliability, using the sum score. Despite that Spearman's and Pearson's correlation coefficients may not be capable to detect systematic differences for the estimation of reliability; in this study, as in many studies, they use them. Hence, high values were reported for both mentioned outcomes (0.99). In this study, the inter-rater reliability was based in the same source of information since the physician had to score via the same videotaped measurement of the patient. Although the methodology of the study was well constructed, including the use of time limits during performance (Wageenar et al., 1989), as drawback may be considered the assessment of upper limb without excluding trunk compensation. Stroke patients and healthy people can reach a target with the same effectiveness; however, stroke patients recruit degrees of freedom from the trunk to compensate the deficit in ROM of upper limb (Cirstea et al., 2000). Hence, trunk restrained must be included in the properly assessment of hemiparetic arm motion or alternatively should be taken under consideration in the final scoring. The inability, therefore, of the scale to quantitatively measure the movement is concluded in the limitation of the outcome measure.

4.2.2 Validity

Excellent concurrent validity was found for ARAT both by Van der Lee et al. (2001) and Yozbatiran et al (2008) in comparison with the motor score of Fugl-Meyer test. In addition Platz et al. (2005) assessed the upper limb function of fifty six subjects who undergone chronic and acute stroke, Multiple Sclerosis and Traumatic Brain Injury using six scales: FMA, ARAT, Box and Block test, Motricity Index, Ashworth Scale and Modified Barthel Index. They also found strong relationship of ARAT with FMT, Box and Block test and Motricity Index. Negative or no significant correlation was highlighted between ARAT and Ashworth scale, the sensation, joint ROM/ pain domain of FMT and the Modified Barthel Index indicating that ARAT is valid for assessing mainly motor function and may not be capable to determine the source of deficit. Subsequently, this notation might negatively affect the planning of the appropriate rehabilitation treatment.

4.2.3 Sensitivity, Responsiveness

Lin et al. (2009) measured upper limb motor function in fifty three stroke patients with four test (ARAT, FM, STREAM, WMFT) at four time points (14, 30, 90, and 180 days post stroke). The ARAT have shown the highest responsiveness in all stage of recovery among the other tests indicating that it can detect small changes between the stages of recovery. The findings of this study also revealed that changes in scores beyond 4 point for the ARAT may indicate real changes in patient’s recovery with 95% confidence. Nevertheless, the ARAT have shown high flooring effects on the acute stage post stroke and ceiling effects on more chronic stage (up to 6 months after stroke), indicating that it may not be appropriate for patients with poor or very good upper limb function.

Other measurement instruments include the Box and Block test which evaluates the gross and fine dexterity of upper limb. In addition the Nine Hole Peg Test is a timed test of upper limb function. It assesses mostly the fine dexterity; the lower the score the better the fine dexterity of the affected UL. Upper extremity function can be also assessed by the Frenchay Arm Test which is consisted of five tasks. A functional upper limb has to achieve a score 5 out of 5 (Higgin et al., 2005). In a similar vein TEMPA (Test Évaluant les Membres supérieurs des Personnes Âgées) includes nine tasks of everyday life thereby assessing the upper limb function (Desrosiers et al., 1993). More focused to the impairment and disability assessment is the UL Motor Assessment Scale (MAS). Despite the limitations of MAS (e.g. ceiling effect), it is widely used in the evaluation of upper limb recovery in stroke patients within clinical settings (Williams et al., 2001). Table 4-3 summarize the function of each of the above mentioned outcome measures.

Table 4-3: Variety of Outcomes Measures for UL Assessment

9 Hole Peg Test	Box& Block Test	Fugl-Meyer Motor Assessment	ARAT	Frenchay Arm Test	TEMPA	(UE)Motor Assessment Scale
Dexterity	Dexterity	Focal Impairment Synergies	Focal Disability	Functional	Functional	Impairment/ Disability

In overall, Fugl-Meyer Assessment, ARAT and the rest scales address a variety of motor functions based on observational techniques leading on bias. Despite the widely use of these scale in clinical trials on measuring upper limb function, there are concerns regarding the ability of the tests to distinguish between restitution of function and compensation (Levin et al., 2009). Also, their lack of sensitivity on detecting small changes may hide important information on recovery or therapy effectiveness following stroke (Vandokum et al., 2013). This drawback on evaluation of hemiparetic upper limb function could be overcome employing motion capture system which offer kinematic analysis and quantitative outcomes. A combination of several kinematics variables may precisely estimate motor changes thereby providing a comprehensive image of recovery after stroke.

4.3 Motion Capture Systems

Motion capture systems are traditionally used for recording human movements. Data acquisition is carried out using passive or active markers attached to anatomical landmarks in the human body. Kinematic data are accurately calculated by the software (Wikipedia; Davis 1988). Two dimensional (2D) and three dimensional (3D) motion's capture systems are currently used from clinician and researches with the latter being more advanced and complex in terms both of software and markers. The fundamental principles of 3D and 2D motion analysis system will be analyzed below.

4.3.1 3D Analysis

The images of two or more 2D cameras are tracked and transferred to a controlling computer where the 3D trajectories are reconstructed. Passive or active markers are used for the determination of the 2D coordinates of each anatomical location (Davis, 1988). Passive markers reflect back light which is emitted from the system camera. They are cheap and light without requiring extra batteries or cables. In contrast with passive markers, active markers are powered themselves to emit their own light. Currently, many systems employ infra-red light due to the fact that it is invisible to naked eye (Anglin et al., 2000). Active markers are more expensive compared with passive markers while they require a battery source or cables attached to the participant's body. Batteries add more weight to the markers and cables tend to affect or limit the performance of the subject thereby affecting the results. However, active markers have great results in capturing over large distance or volumes (O'Nolan , 2013).

Vicon system has been well characterized as the gold standard of 3D motion analysis system. The T-series cameras have high resolution up to 16 megapixels being able to capture at up to 120 fps (Vicon 2013). T- Series cameras use infra-red light-emitting diodes strobes. The accuracy and the processing time of the data are the most important factors for choosing a 3D motion capture and analysis system. Ehara et al. (1997) studied the accuracy of 3D camera systems. He reported that for Vicon system the mean error was 0.94 mm and the data processing time was 15 sec. Comparing to the other 3D system, Vicon was the most accurate. However, Vicon employed 6 cameras while the other systems were using 2 or 4 cameras thereby having advantages on tracking the marker's coordinators (Ehara et.al, 1997). Nine motion capture and analysis systems were evaluated in 2002 in the comparison meeting held at Nippon Engineering College, in Tokyo. Contrary to Ehara, the systems were compared for their performance both in sport and in entertainment fields. The results indicated that Vicon system had the minimum value for the average absolute error for the measurement of the accuracy of distance between two points, of angle and of the virtual points. Hence, Vicon was the most accurate motion analysis system among the rest systems.

4.3.2 2D Analysis

Two dimensional analysis systems use simple markers such as paper circle which can be tracked by the software. A camera is appropriate for 2D motion analysis work if it has a shutter speed 1/500 sec or faster for the prevention of blurring. Furthermore, it must have a manual focus setting. If markers are used, the diaphragm should be adjusted to improve contrast with the background.

Norris et al studied concurrent interrater, intrarater and test-retest reliability of 2D video analysis in the measurement of sagittal plane angles at the knee and the hip during mechanical lifting. They found excellent inter- and intrarater reliability (ICC> O.91) for both hip and knee flexion angles; for test-retest reliability the values of ICC were 0.79 and 0.91 for hip and knee flexion respectively. Therefore, they concluded that 2D video analysis system could be objectively measure angles during functional task thereby providing a reliable outcome tool for clinical use. However, this study had limitations such the fact that the participants were only female subjects and the validity of the system was determined by comparing the 2D kinematics with a goniometer (Norris et al., 2011). 2D kinematics has a lower intra-subject variability compared with inter-subject. The average standard deviation (degrees) and the coefficient of variation (percentage) are used as means of measurement of the joint angles variability. The latest demonstrate weakness as mean of variability’s measurement (Kirtley, 2006).

4.3.2.1 Limitations

There are two limitations which must be taken under consideration in 2D analysis techniques.

Parallax Error

This type of error occurs when the range of motion has a large deviation from the optical axis of the camera. Hence, as the object is moving towards the periphery of the camera image, the parallax error is increasing. Undoubtedly, it’s impossible totally eliminated this error. However, it can be minimized by fitting the central part of the movement with the optical axis of the camera while zooming the lens to record the area of the motion in the most interest (Kirtley, 2006).

Perspective Error

The perspective error occurs when changes in the length of moving segment are observed due to the out-of the calibrated plane movement. The more far away from the calibrated plan is the motion performed, the more the error increases. Furthermore, the perspective error is proportional to the distance between the camera and the subject. Hence, for eliminating the error, the camera should be placed as far as possible from the motion plane and in restrict perpendicular position regarding on the calibrated plane. Although, in 2D analysis, it is presumed that all the motion is performed in the calibrated plane, several medical condition and disorders do not obey this assumption. For instance patients with spasticity or musculoskeletal deformities are not able to complete a task strictly in one plane (e.g. sagittal plane), further contributing to increase the perspective error. However, this error can be estimated and corrected by observing the alterations in segment length; increase or decrease confirmed out- of plane motion (Kirtley, 2006).

4.3.3 Electromagnetic Systems

Apart of video-based motion analysis systems, kinematic analysis of upper limb motion have been also carried out using electromagnetic systems. These devices produce three orthogonal low frequency electromagnetic fields which are detected through many small receivers. Electromagnetic systems have the advantage of providing fast, three dimensional data however their drawbacks include sensitivity to metal appliances, limited distance of recording (approximately three meters) and patient’s connection with the hardware unit. Finally, owing to only a single sensor attached in each segment, the problems with skin movements cannot be overcome. The ‘’Polhemus FASTRAK’’ device and the ‘’Flock of Birds’’ are electromagnetic systems which have been employed in studies for the measurement of upper limb kinematics (Murray, 1999; Biryukova et al., 1996; Meskers et al., 1999).

4.4 Clinical Relevance of Kinematics Analysis in UL Assessment

The nature of upper limb motion differs from human's gait patterns due to complexity and variability of arm tasks. Therefore, compared with the gait analysis, upper limb motion analysis is more difficult. Opposed to standardized and stereotyped gait cycle, upper limb's functional tasks exhibit a larger variation among the healthy population (VanAndel et al., 2008). Thereafter, specific kinematics models for upper extremity are crucial for sound outcomes. In a similar vein, accurate quantitative analysis of upper limb motion is essential for understanding the recovery after stroke. The majorities of studies involved with the evaluation of upper limb movements in stroke patients employ assessment scales but only few use kinematic analysis (Kamper et al., 2002). The reasons under this fact are the high cost and the limited availability of 3D motion analysis labs in combination with the lack of validation of 2D capture system in assessing the hemiparetic upper limb kinematics. However, the clinical relevance of UL kinematic analysis has been well established in medical research field for improving the rehabilitation approaches following stroke.

Recently, Dokkum et al. (2013) studied the contribution of kinematics in the assessment of upper limb function after stroke. Thirteen patients in early post stroke stage (<30 days) demonstrated a reach to grasp task while 3D kinematics were recording by the Fastrack magnetic field. The results depicted that the following selected kinematics variables could detect changes between the assessment sessions; movement time, trajectory length, maximum velocity and number of velocity peaks were calculated. The timing of peak velocity and the duration of movement provide information about the recovery. Following rehabilitation, the duration of reaching movement was decreased while the maximum velocity was occurring earlier in the acceleration phase of reaching, thereby showing motor recovery. Furthermore, over rehabilitation, kinematics analysis has shown straighter trajectory paths and fewer velocities peaks. Both of these finding demonstrate more smoothly and irregular upper limb movements. Comparing the kinematics analysis to Fugl-Meyer test scoring was found that kinematics provides more accurate and objective outcomes in upper limb motor assessment in acute stroke patients. In this study the trunk was constrained so no information regarding the compensation of trunk was available. Thereafter, a clinical useful assessment may require either the trunk movement in order to avoid potential pain and discomfort resulting from the lack of compensatory movement thus affecting the results.

In line with Dokum et al. observations, Hingten et al (2006) examined the effectiveness of a 3D kinematic model for the motion analysis of upper limb in stroke patients. The model could obtain information regarding the angles of trunk, shoulder and elbow movement. This model was employed in this study in order to compare kinematic variables of the affected and non-affected upper limb of stroke patients, using a 15- camera Vicon System. The results were confirmed that the unaffected upper limb has in overall larger range of motion and significant higher values of angular velocity than the affected arm. The 3D model was validated for the use in assessment of upper limb recovery in stroke patients.

Many researches (Van Andel et al. 2008; Murphy et al.2011) argued about the objectivity of kinematics variables in the assessment of upper limb motor performance. However, the majority of them were using 3D analysis resulting in poor knowledge about the effectiveness of 2D analysis on measuring Kinematics of upper extremity.

5 Literature review of comparison 3D and 2D studies

It is evidence that the use of 2D analysis in clinical trials is limited because of its lack of formal validation. Of our knowledge, there is only one investigation (Yang et al., 2013) which compared the performance of 2D system with the 3D one in connection with the upper limb function while there are a limited number which have undergone comparisons focused on lower limb movements.

Cornwall et al. (1995) studied the validity of 2D analysis in comparison with 3D analysis regarding rear foot motion during walking. Results from both systems showed the same rear foot motion for the initial 60% of the stance phase. They concluded that 2D can be employed for the evaluation of rear foot motion during walking. Nevertheless, this study recruited only healthy participants thereby no subject with pathological gait pattern was assessed. Another, limitation is the fact that the agreement of 3D and 2D analysis systems was restricted during the stance phase. Therefore, further studies for the validation of 2D analysis should include the assessment of pathological gait patterns during the gait cycle.

Nielsen et al (2008) conducted a study related to the agreement between 2D and 3D analysis system about angular measurements during gait. They recorded angles of knee and ankle in sagittal plane using concurrently 3D video and a single camera. The results highlighted high intra-class correlations for the knee and ankle angles during swing phase. However, overall there were significant differences between the two types of video analysis for both the ankle and knee angles. Hence, it was deduced that the software used for the 2D analysis [Hu-m-an] it is not valid and it was suggested that further studies would be required.

Recently, Ugbolue et al (2013) conducted a study for the evaluation of a 2D video based portable system (AVPS). This system was compared with the gold standard of motion analysis, Vicon system, both statically and dynamically. Twelve healthy subjects were recruited for the needs of this investigation. Gait analysis was recorded simultaneously by the 3D Vicon system and the AVPS. The latter included a walkway grid mat made of vinyl flooring, flat paper bull's eye markers, four photoswitches mounted on tripods, a light-indicator, a video camera, and a computer with ProTrainer System software. The kinematics results showed no significant difference between the two video systems ($P > 0.05$). Furthermore, intra- and interrater reliability were highlighted for both the temporo-spatial and kinematics variables. The researchers concluded that AVPS can be employed in clinical settings for healthy people thereby providing reliable and valid results. AVPS is simple, low cost and quick to set up, however a limitation regards the manual data processing procedure. Also, as all the 2D video analysis system, the perspective error has to be taken under consideration. Finally, the sample size of this study was relatively small and the participants were all normal people.

Yang et al. (2013) suggested a new portable simple-camera system to assess upper limb movement. In their study, they found good limits of agreement on upper extremity motion between the proposed system and the gold standard 3D Vicon system. Trunk- tilt, shoulder and elbow movements both in healthy and stroke patients can be accurately captured by the proposed 2D system.

As extension of Yang’s et al investigation, we conducted the current study using the proposed 2D video system and Vicon system for the assessment of shoulder-elbow coordination and trunk forward tilt in stroke and healthy subjects. We aimed to evaluate the agreement between these systems targeting the potential use of a portable single camera in clinical trial for the quantitative assessment of upper limb following a stroke. Such an establishment could provide the researches with an objective, cheap and easy administrative outcome measure thereby improving the evaluation of the under investigation rehabilitation or/ a pharmacological treatments of the hemiparetic upper limb.

6 Materials and Methods

6.1 Participants

This study was approved by the University of Strathclyde Ethics Committee. The study took place in the Biomechanics Lab in the Biomedical Engineering department of the Strathclyde University. The participants were five healthy adults and five stroke survivors. All participants were adults with an average age 42.55 ± 14.75 years old. Participants’ anthropometric data are shown in table 1. Stroke survivors were recruited from stroke groups in Glasgow supported by Chest Heart and Stroke Scotland (CHSS). Stoke subjects were included in the study if they have suffered a stroke at least 12 months ago resulting in an upper limb impairment. Individuals should also be able to understand and follow simple instructions such as *‘’touch the cup with your hand’’.* Participants with medical history of any musculoskeletal problem which would limit the range of motion of their upper limb were excluded from this study. A consent form and an information sheet have to be read and signed by the participants prior to taking part in the research (Appendix 1).

Table 6-1: Participants' anthropometric data (Means and Standard Deviations)

Weight (Kg)	**Height (cm)**	**Age (Years)**
75.7±11.4	**1.71±0.1**	**42.55±14.75**

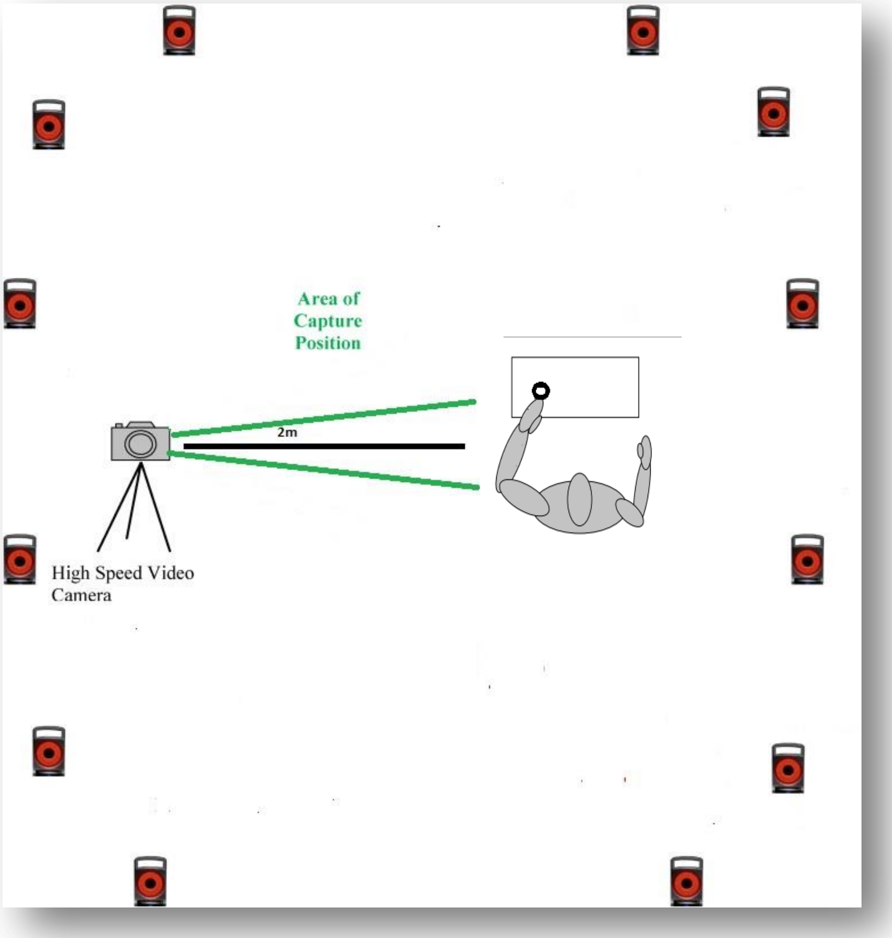

Figure 6-1: Laboratory Configuration

6.2 Hardware

The three dimensional analysis was carried out using the Vicon system with 12 infra-red cameras T- series(6 x T40 and 6 x T160, Oxford Metrics, UK) , sampling at 100 Hz. A digital camera (EX-FH20 EXILIM, Casio) on high speed mode (210 fps) with 360x480 resolutions was used to capture two dimensional video analyses.

6.3 Proposed system-2D

The proposed system is a portable single camera motion analyses system (Cheng et al, 2013). High speed (210 fps) camera was used to avoid blurring effect. Camera calibration took place to remove the distortion effects. Marker tracking was started with the selection of template markers for each of the five anatomical points (neck, shoulder, elbow, wrist, and waist). Due to high proximity between the markers (fig. 1) the definition of the search area (SA) was crucial for the avoidance of tracking confusion.

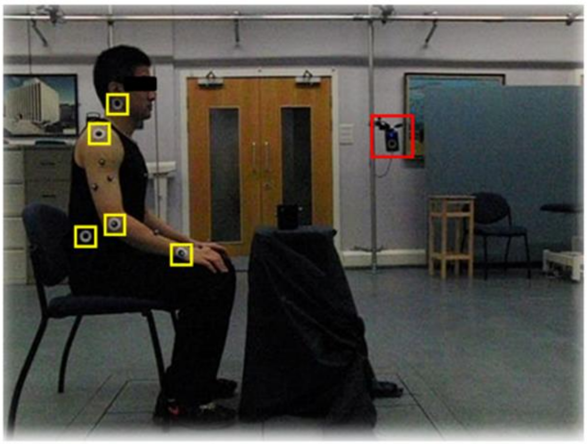

Figure 6-2: Experimental camera scene (Cheng et al., 2013)

Moreover, tracking was challenging both due to changes in the appearance of the markers during the joint rotations and due to simultaneously movement of the marker with the limb (*object-on-object* problem). Thus, a Kalman filter was applied to determine the initial SA. Subsequently, each marker could be detected using Structular Similarity (SSIM) image quality assessement algorithm, thereby achieving the *object-on -object* problem.

6.4 Protocol

Participants were asked to perform a reach to grasp movement while the motion was tracked and recorded by the two systems.

Vicon system:

Retro-reflective markers adhered to participant’s upper limb (hemiparetic arm for stroke patient) using the following marker arrangement. Figure 6.2 illustrate the marker placement from front and rear view.

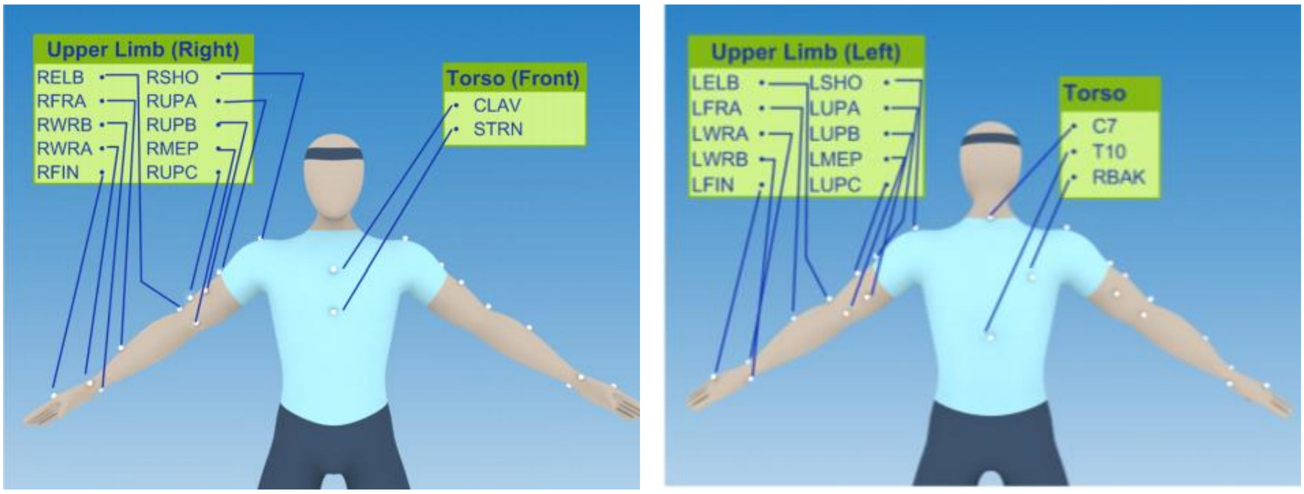

Figure 6-3: Upper limb model marker placement-front view and rear view (Upper Limb Model, Product Guide-Vicon)

The markers were attached directly to the skin and clothes of each participant using double side sticky tape. Tables 6.2 and 6.3 define and describe the marker placement in more details.

Table 6-2: Torso Markers for left UL

Marker Label	Definition	Marker Placement
C7	7th cervical vertebra	On the spinous process of the 7th cervical vertebra
RBAK	Right back	Over the right scapula
T10	10th thoracic vertebra	On the spinous process of the 10th cervical vertebra
CLAV	Clavicle	On the jugular notch
STRN	Sternum	On the xiphoid process

Table 6-3: Left UL Markers

Marker Label	Definition	Marker Placement
LSHO	Left shoulder	On the acromio-clavicular joint
LUPA	Left upper arm marker A	On the lateral upper left arm[1]
LUPB	Left upper arm marker B	On the lateral upper left arm[1]
LUPC	Left upper arm marker C	On the lateral upper left arm[1]
LELB	Left elbow	On the lateral epicondyle[1]
LMEP	Left medial epicondyle	Left humerus medial epicondyle
LFRA	Left forearm	On the lateral left forearm
LWRA	Left wrist marker A	At the thumb side of left radial styloid
LWRB	Left wrist marker B	At the little finger side of left ulnar styloid
LFIN	Left finger	Below the left third metacarpus

[1] Technical reference frame

Video analysis:

For the video tracking, bulls-eye black and white markers (Fig. 3) were attached to following anatomical points.

- Mid iliac crest [pelvis]
- Radial styloid process [wrist]
- Lateral epicondyle of humerus [elbow]
- Lateral border of the acromion process [shoulder]
- Tragus of ear [head]

If the reflective and paper marker were overlapped, we followed the configuration proposed by Ugbolue et al. Therefore, the reflective markers were placed directly above and on the center of the paper label (Ugbolue et. al, 2013). The bulls- eye markers form the following angles (fig. 6-4)

α: angle between elbow- shoulder line and elbow- wrist line

β: angle between waist- neck line and vertical line

***γ*:** angle between waist-neck line and shoulder – elbow line

Angles *α, β* and *γ* were calculated according to coordinates of the five bull- eyes markers. Angle *α* indicates the angles of flexion- extension in the elbow, angle *β* the flexion-extension angles of shoulder and angle *γ* provides the trunk tilt angles in sagittal plane.

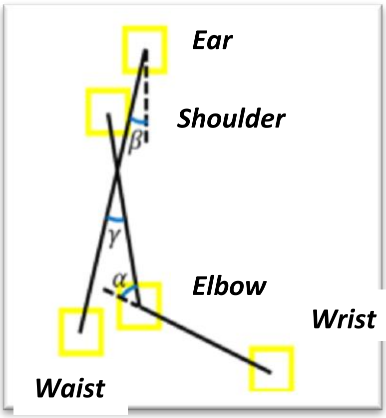

Figure 6-4: Angles' configuration (Chang et al., 2013)

6.5 Methodology

Participants sat in an armless chair in front of a table in the middle of the biomechanics laboratory with the arm relaxed on the table. The camera was mounted on a tripod and position 2m from the subject in line with their elbow. They were asked to perform a *drinking- tea motion (Fig. 5)*. They had to take a plastic cup from the desk, carry it towards their mouths and place it back again on the starting position. The cup was placed directly in front of them at a distance equivalent to 80% of their maximal reach which was tested before hand arm length. The upper trunk was not restrained allowing it to move normally. The instruction was *''reach and bring the cup to your mouth''.* Participants with a deficit of grasping were asked simply to touch the plastic cup and move their hand towards to their mouth, as best as they could. Each subject had to complete 5 trials.

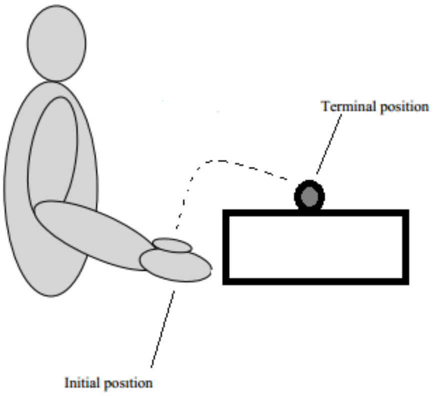

Figure 6-5: Task definition of reaching movement

6.6 Data Analysis

Kinematics data of the upper limb and the trunk were recorded simultaneously with the 2D video camera and the Vicon system. Analysis of the data was divided into two steps. First, the temporal coordination between shoulder and elbow and second the forward movement of the trunk were analyzed. The data of each trial of the five healthy subjects and the five stroke patients were plotted (fig. 6-6 and 6-7). In this point has to be mentioned that the data of one of the five stroke patients were not included in the analysis because the patients was not able to completely perform five trials. Therefore, four stroke participant's data were used for the statistical analysis. The angles were calculated for one DOF of the shoulder (flexion-extension), one DOF of the elbow (flexion- extension) and one DOF of the trunk (flexion-extension) in the sagittal plane. Both variables include data from health and patient participants.

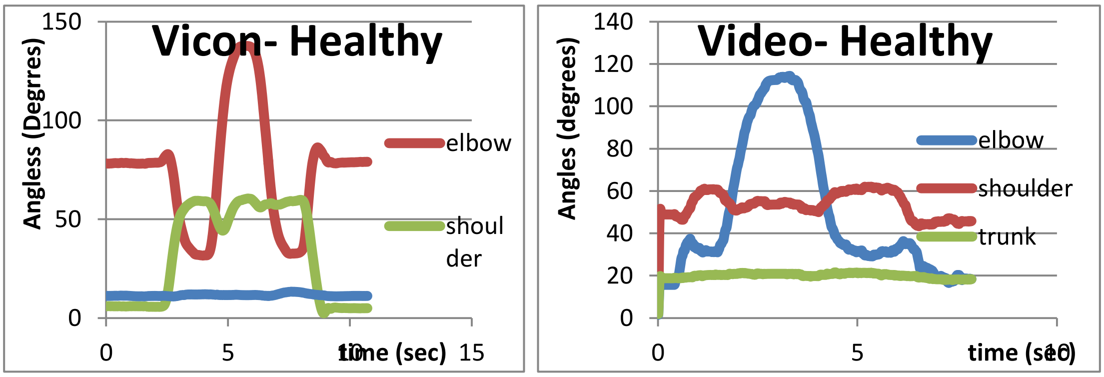

Figure 6-6: Example of plotting shoulder-elbow-trunk movement. Data from a single trial (Healthy subject)

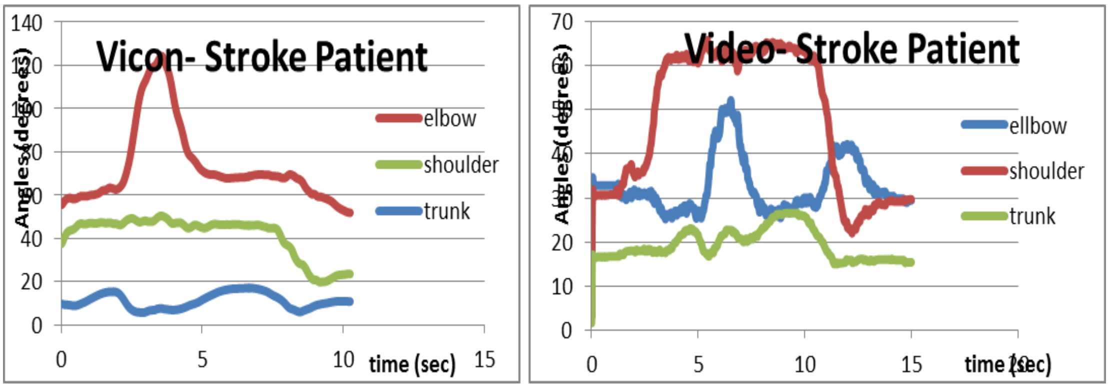

Figure 6-7: Example of plotting shoulder-elbow-trunk movement. Data from a single trial (Stroke Patient)

The angles of the joints were computed from the position data as the angles between the corresponding vectors joining adjacent markers. The principles movement axis for the shoulder and elbow was the x-axis while for the trunk tilt was the z-axis. In particular, for Vicon system's data, retro-reflective markers on shoulder, elbow and wrist were used for the calculation of upper limb coordination; markers on 7th cervical and 10th thoracic spine vertebras were recording the trunk angles. In a similar vein, angles *α, β* and *γ* corresponded on elbow, trunk and shoulder angles respectively, for the video system.

Interjoint coordination was estimated by constructing a graph angle/ time including the shoulder and elbow angles during the reaching task. Subsequently, the temporal overlap between the two joint was calculated. Onset of the movement was defined as the time at which each joint angle was exceeded three deviation of the baseline. On the other hand, reaching offset was determined as the time at which the first peak of finger marker was recorded. For the trunk tilt, a graph of trunk angles/time was constructed and the maximum angle of forward trunk tilt was found. However, trunk movement was defined as the maximum angle value during the reaching task minus the angles of the initial position. The results of video were compared to those obtained from Vicon using statistical analysis. The final analysis may provide information about the effectiveness of the 2D proposed video system to assess accurately the coordination of upper limb and the compensation of the trunk during a reaching task. Also may provide insights into the ability of 2D video detecting difference for the analyzed kinematic variables between healthy population and stroke patients.

6.7 Statistical Analysis

Before any type of statistical analysis, a data screening was preceded. This procedure assesses the normality of data (Appendix 2) regarding whether we can follow the assumption that the data are a sample from a population with Normal distribution. In this wave, the Ryan-Joiner normality test was employed (Minitab Software) for assessing the normality of the data. According to the test's results, we used parametric or non-parametric statistics to identify whether or not the proposed 2D video could accurately measure the upper limb coordination and trunk tilt, both on healthy and stroke subjects.

Although the majority of statistical analysis in medical research is based on hypothesis testing, this type of analysis was not included in this study due to the small sample size. A small sample may not have the sufficient power to detect a difference between the two systems (Video-Vicon) thereby there was a risk for type II error (false negative) (Altman, 1992). Hence, in case that there was no evidence to reject the null hypothesis when is false, this would mean that there is no difference between the outcomes of 2D video and Vicon system, when in fact exists. In this vein, confidence intervals were used for studying the mean difference of the outcome measures.

7 Results

The result of the Normality test indicated that the data were compatible with a Normal Distribution hence a parametric methods was chosen for statistical analysis. Table 7-1 shows the P- values and Ryan- Joiner values of the normality tests. All the P-values were greater than 0.05 with the majority of them having values even greater than 0.1. The data of difference (DIF.) between the two systems on measuring trunk tilt both in healthy (H) and stroke patients (P) are appeared with the lower P-values.

Table 7-1: Ryan joiner test for the data of trunk tilt (left) and UL coordination (right)

Trunk tilt	R-J	Probability (P)
H-Video	0.962	>0.1*
H-Vicon	0.985	>0.1*
H-DIF.	0.896	0.089*
P-Video	0.989	>0.1*
P-Vicon	0.947	>0.1*
P-DIF.	0.889	0.079*

UL Coordination	R-J	Probability (P)
H-Video	0.998	>0.1*
H-Vicon	0.959	>0.1*
H-DIF.	0.948	>0.1*
P-Video	0.939	>0.1*
P-Vicon	0.986	>0.1*
P-DIF.	0.924	>0.1*

***P> 0.05 indicates Normality**

Since it has been proved that the data were a sample from a population with a Normal Distribution, the mean and standard deviation for each variable were calculated (Table7-2). Upper limb coordination was expressed as the percentage of the shoulder-elbow temporal coupling during the reaching task. An increase of 3.95% (±7.42) and a decrease 4.95% (±8.71) were observed by video recordings on upper limb coordination for healthy and stroke patients, respectively. Accordingly, trunk tilt difference for healthy participants was found 0.415 (±0.415) degrees and for stroke patients 1.20 (±2.46) degrees.

Table 7-2: Mean and S.D values of all the variables and the outcome measures

Variables	Outcome measure	Healthy Mean (S.D)	Stroke Patients Mean (S.D)
UPPER LIMB COORDINATION (%)	**VIDEO**	*81.11 (5.36)*	*69.30 (15.82)*
	VICON	*77.16 (2.97)*	*74.25 (7.56)*
	DIFFERENCE	*3.95 (7.42)*	*-4.95 (8.71)*
TRUNK TILT (degrees)	**VIDEO**	*2.399 (0.601)*	*8.09 (2.43)*
	VICON	*1.955 (0.471)*	*6.89 (3.14)*
	DIFFERENCE	*0.415 (0.415)*	*1.20 (2.46)*

Table 7-3 describes the 95% confidence interval for all the outcomes. The majority of the variables show wide intervals with an exception in coordination of upper limb in the healthy subjects. However, the mean difference for trunk tilt in stroke patients is 1.20 degrees with 95% confidence intervals -2.72 to 5.12 and for UL coordination is -4.95% with 95% confidence intervals -18.8 to 8.9, indicating good agreement between video and Vicon in trunk tilt.

Table 7-3: Confidence Intervals (α= 0.95)

Coordination	**95% CI**
H-Video	*(81.11, 74.45- 87.77)*
H-Vicon	*(77.16, 73.46- 80.84)*
H-Dif.	*(3.95, -5.25- 13.16)*
P-Video	*(69.30, 44.13- 94.47)*
P-Vicon	*(74.25, 62.2- 86.28)*
P-Dif.	*(-4.95, -18.8- 8.9)*

Trunk tilt	**95% CI**
H-Video	*(2.399,1.65- 3.14)*
H-Vicon	*(1.955, 1.37- 2.54)*
H-Dif.	*(0.415 ,-0.1- 0.93)*
P-Video	*(8.09, 4.21- 11.95)*
P-Vicon	*(6.89, 1.88-11.88)*
P-Dif.	*(1.20,-2.72, 5.12)*

In addition, figures 7-1 and 7-2 illustrate the interval plots for the mean of the variables, including the mean of the difference between the video and the Vicon system for both the healthy subjects and stroke patients.

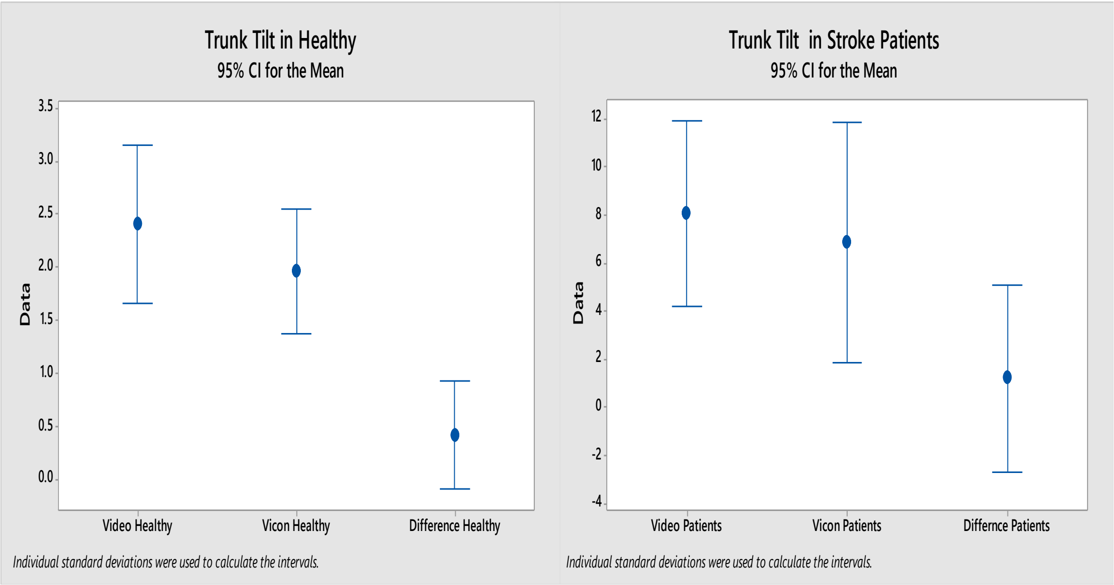

Figure 7-1: Interval plots for the trunk tilt

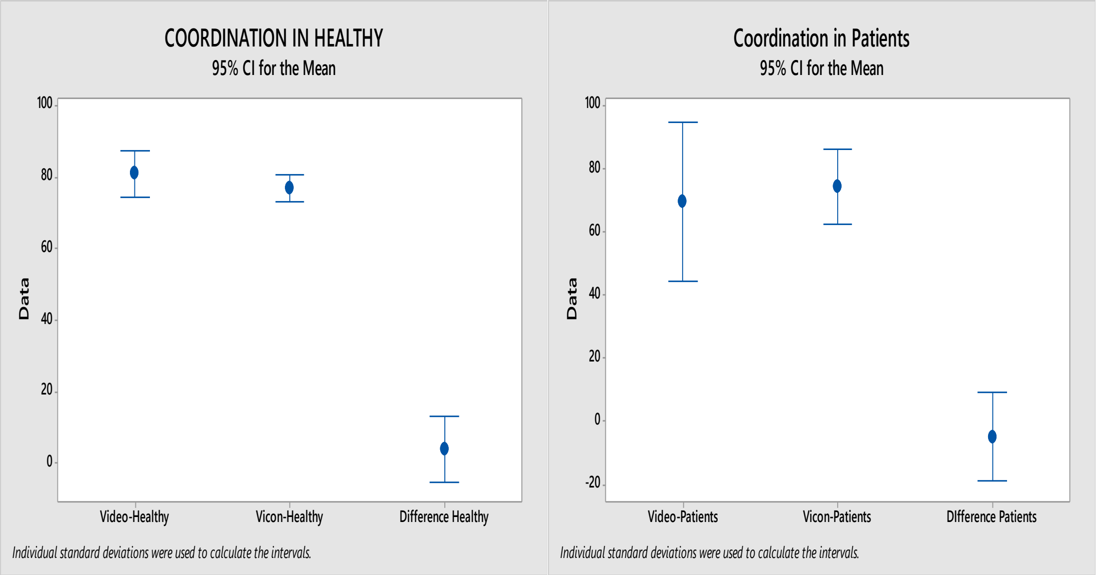

Figure 7-2: Interval plots for the UL coordination

Figure 7-3 depicts the Normal Distribution of Video and Vicon data. For all graphs the blue line represents the video recordings and the red-dashed line describes the Vicon data. It is clear that video overestimate all the values, as the video means' values shift to the right; only for the UL coordination in stroke patients there was underestimation of the values by the video. As the distance between the means of the two systems increases, the accuracy of the proposed video system decreases.

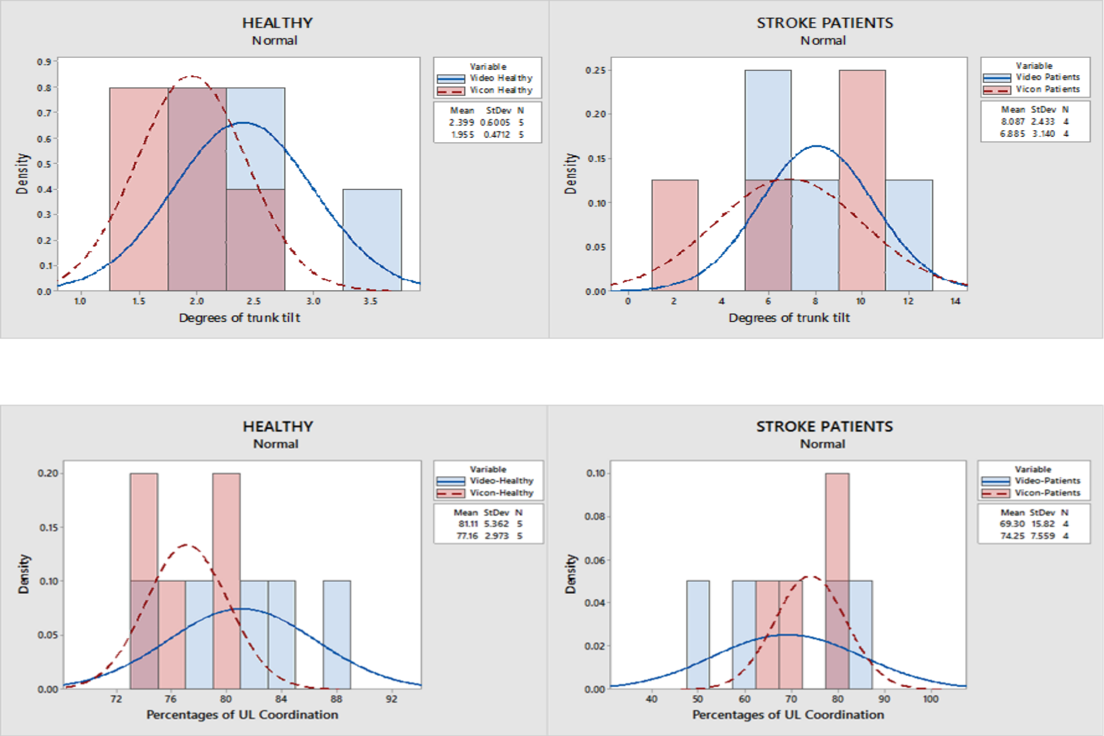

Figure 7-3: Video and Vicon Normal Distribution Plots for the trunk tilt (upper part) and the UL coordination (lower part).The red and blue lines illustrate Vicon and Video data, respectively.

Furthermore, the accuracy and bias of the proposed 2D system is illustrated in figures 7-4 and 7-5. Opposite linearity is observed for the coordination of upper limb between healthy and stoke patients while an approximately horizontal line for the trunk tilt in healthy subjects is illustrated.

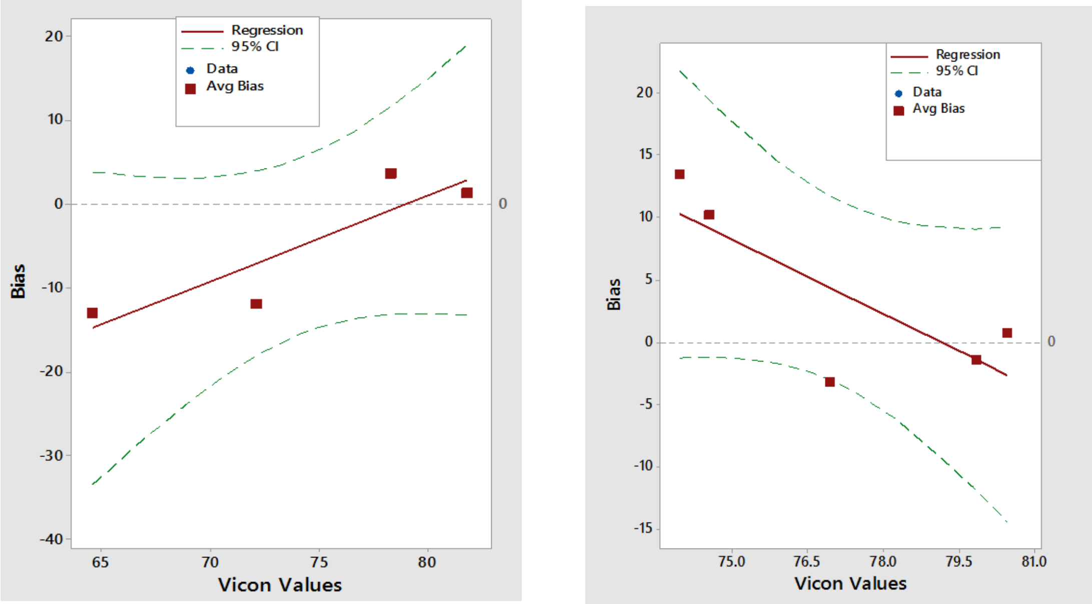

Figure 7-4: Accuracy and Bias of Video data for the coordination of the UL in Healthy (right) and Stoke patients (left)

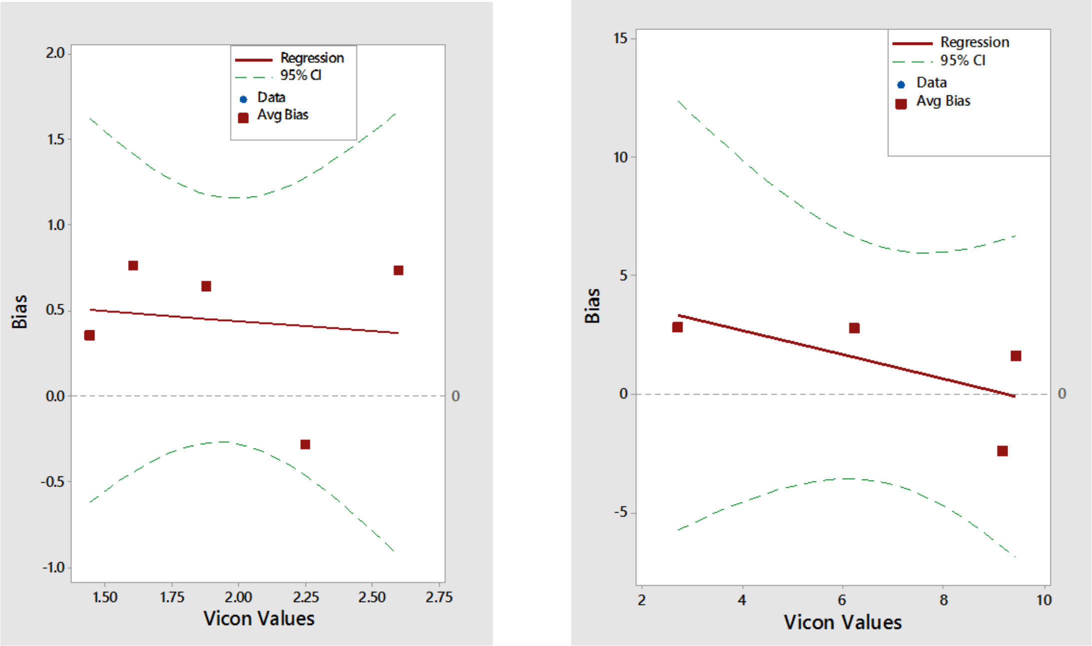

Figure 7-5: Accuracy and Bias of Video data for the trunk tilt in Healthy (left) and Stoke patients (right)

This study aimed to compare a 2D single camera system to the ''gold standard'' in 3D Vicon motion analysis system for its potential use in upper limb assessment in stroke patients. The results have shown better agreement between the two systems for the measurement of trunk tilt compared to upper limb coordination in stroke survivors. However, a number of limitations existed in this study which will be addressed in the next chapter.

8 Discussion

In this study the upper limb of five healthy and five stroke patients were assessed simultaneously by a 2D video system and the 3D Vicon system during a reaching tasks. Reach to grasp movement was chosen because it found that it simulates the amplitude and the frequency of the movements in daily living (Thies et al., 2007). Reaching task was also chosen because includes the coordination of multiple joints and it's also a movement which has to be reacquired after stroke (Hingtgen et al., 2006). The main objectives of the currently study were to (1) compare the coordination of the upper limb and the trunk tilt recorded with 2D video and 3D Vicon motion capture system in stroke patients, (2) identify if the coordination of the upper limb and the trunk can be recorded with a single camera system both in healthy and stroke subjects and (3) finally, if the 2D video system has the potential to replace the gold standard Vicon system in the hemiparetic UL assessment in research field.

8.1 Upper limb Coordination

8.1.1 Comparison 2D video - 3D Vicon in Stroke patients

Comparing the mean values of the difference between video and Vicon in stroke patients, it appears that the two systems recorded similar values for the percentage of upper limb coordination. The single- camera underestimated the hemiparetic upper limb coordination by 4.95%. Despite the relative low mean difference, video data had a notable greater variation (15.82 %) compared to Vicon (7.56 %). In addition, the standard deviation of the mean difference between the systems was almost two times the mean value (8.71%), indicating that the mean value of the video-Vicon difference is not such an accurate representation of the measurement due to the high variability.

Wide 95% confidence interval for both the video system and the difference of systems in stoke patients show that video have some limitation in accurate prediction of upper limb coordination in people with impairment. Yang et al. found wide upper and lower limits of agreements for the elbow angles which confirm that there are notable deviation between the elbow movement plane and the camera scene plane. The deviation might be amplified in case that elbow movements have lost their smoothness and normal trajectories. Studies showed that elbow trajectories in stroke patients are more segmented and dispersed than in healthy subjects. (Cirstea et al., 2000; Steenbergen et al., 2000). Also, the timing and trajectory of movements are affected by coordination deficit (Shumway-Cook and Woollacott, 2002). In addition, it is known that the hemiparetic upper limb is characterized by pathological movements in fixed pattern (Lenin, 1996). This pattern includes coactivation of shoulder abduction-elbow flexion and shoulder adduction-elbow extension. In any effort by the stroke patient to extent the elbow in reaching task, a part of UL movement will be occurred in frontal plane, since shoulder abduction-adduction occurs in the frontal plane (Dewald et al., 2001). Taking the above under consideration it seems to be likely that upper limb coordination might be poorly recorded by the video, as it capture only movement in sagittal plane.

8.1.2 Comparison 2D video between Stroke patients - Healthy

In contrast with stroke patients, upper limb coordination in healthy was overestimated by the video system (3.95 ± 7.42 %). The narrow 95% CI for both video (81.11, 74.45- 87.77) and Vicon (81.11, 74.45- 87.77) in healthy people means that the 95% of the mean value of the healthy population will lie within narrow upper and lower limits thereby both video and Vicon recordings of upper limb coordination are likely to be true in healthy people. The fact that the mean and 95% CI of the difference of two systems approaches and even cross the zero (3.95, -5.25-13.16) explain the good agreement of video and Vicon on the evaluation of upper limb coordination in healthy individuals.

Less video bias for both healthy and stroke patients is observed on well coordinate upper limb. As the percentage of UL coordination decreases the bias increases; however, positively for the healthy participants and negatively for the stroke patients. Cirstea et al., suggested that, in their study, stroke patients with mild UL impairment had interjoint coordination and movement trajectories similar with healthy participants. In line with our findings, a single camera system would be likely to be employed in upper limb assessment of healthy and mild impaired stroke patient. However, more studies have to be carried out to confirm this prediction.

8.2 Trunk Tilt

8.2.1 Comparison 2D video - 3D Vicon in Stroke patients

The video system tends to give higher recordings in trunk tilt of stroke patients compared to Vicon. The mean difference between the two systems is 1.2 degrees with 95% confidence intervals -2.78 to 5.12. Despite the fact that the findings indicate wide intervals, it can be noticed that the values lie around zero. Additionally, there is an overlap between video and Vicon data, thereby meaning that both systems include similar values of trunk tilt. Therefore, single camera appears to have good agreement with Vicon system in the measurement of trunk tilt in stroke patients. In a same vein, Yang et al. (2013) concluded that the proposed 2D video and the Vicon system have shown good limits of agreements in trunk tilt for both stroke and healthy participants. They also found that the deviations between the trunk tilt plane and the camera scene plane were not very notable.

The results show that the proposed video overestimates the trunk tilt in stroke patients. The mean values for forward trunk movement obtained from video and Vicon were 8.09° and 6.89°, respectively. This could be attributed to the anatomical points where the markers were attached. Analytical, trunk tilt was recording both by two bull-eye markers (video) placed on ear and on pelvis and two reflective markers (Vicon) placed on 7th cervical and 10th thoracic spine. Therefore, the data obtained from the markers for the video included extra movements of head and pelvis. It is known that stroke patients typically sit with posterior tilt of the pelvis in order to compensate the weakness in the abdominal muscles. As an extension of the backward tilt, they keep a kyphotic posture in the thoracic spine and a head forward position. Furthermore, the asymmetrical weight- bearing on the buttocks causes a lateral trunk flexion and lateral pelvic tilt (Bobath 1978; Devis, 1988). Taking all the above under consideration, it can be derived that 2D video model might measure bigger angles for trunk tilt due to the abnormal sitting posture of stroke patients. The lack of this abnormal posture in healthy people might explain the better agreement between video and Vicon data for the trunk tilt (0.415 degrees of difference).

Comparison of S.D values showed that for trunk tilt video system displayed less variation than Vicon data in stroke patients. Ehara et al. (1995) compared the S.D in mm error between several motion analysis systems which have been proposed for the clinical field. The results of the study revealed that Vicon had one of the lowest S.D among valid capture systems. In addition, Richard (1999) investigated the agreement between seven commercial capture systems including Vicon system. The average error for all systems on measuring the actual angle value was 3 degrees with Vicon system demonstrating the lower error in angular measurement (1.41 degrees). Therefore, since Vicon is assumed valid tool for clinical use and it has been proved that displays low error values for angular and linear displacements, the variation of proposed video could be acceptable in clinical field.

8.2.2 Comparison 2D video between Stroke patients - Healthy

When mean values from video were compared between healthy and stroke patients, the average trunk tilt in healthy participants was 2.39° and in stroke survivors was 8.09°. The results suggest that video recordings in stoke patients were approximately 2.5 times greater than in healthy. Hence, video can measure changes in trunk compensation between healthy and disable people. In addition, comparing the average bias on fig.7-5, it results that trunk tilt for both healthy and stroke patient was positive biased. However, there was a negative relationship between trunk movement and video bias in stroke patients, indicating that video data appears to be more accurate in stroke patients who were perform greater trunk compensation. On the other hand, video has shown a notable low bias and less variation in trunk tilt data of healthy people. It would seem that the overall bias of single camera on the trunk compensation is relatively low for both healthy and stroke patients thereby being more accurate in stroke patients with more trunk movement. Cirstea et al. (2000) found that stoke patients with moderate and severe impairment (low Fugl- Meyer scores) recruit more forward trunk movement during a reaching tasks. Consequently, video system might have the potential to accurate assess stroke patients with severe or/ and moderate impairment.

8.3 Limitations

The main limitation of this study regards the sample size. Five healthy and five stroke patients were recruited for the purpose of this investigation. From those five stroke patient, only the data of four patients were included in the analysis and subsequently in the results; the fifth stroke patient was unable to complete the trials. The limited sample size weakened our findings in terms that simple statistic methods were used to compare the data. However, this direction was chosen knowing that false accepted confidence intervals are less dangerous than incorrectly accepted P-values and hypothesis testing. Undoubtedly, a future study with an acceptable sample size for more advance statistical analysis would be useful to carry out.

Limitations also existed within the protocol. The subjectivity of palpation of anatomical landmarks for marker attachment was depending on the individual builds. Furthermore, skin or clothes movement might cause a relative displacement between markers and overlying bones. Unfortunately, this cannot be eliminated but with the proper movement calibration could be compensated (Aglin et al., 2000).

During data analysis on upper limb coordination, a few assumptions had to be done. As it was described earlier in data analysis section, the offset of reaching movement was determined by the trajectory of the marker on finger for the Vicon system. However, this assumption was not possible to occur for the video data. The subjectivity of the user on determining the end of the reaching movement may be a source of bias between the systems. In particular, the possibility of the presence of this error might be more likely observed in stroke patients since the curves of elbow and shoulder movements are not clearly shaped. The limitation regarding the offset of the reaching movement could have been avoided by the employ of switches. This kind of switches had been used in the past in clinical trials and their role was to determine the onset and offset of the movement for acquiring more precise data.

In general, one common drawback of 2D motion analysis is the use of single plane recording. This includes two issues: the inability of video to detect a marker in case it is obscured and in case the movement occurs in different plane. Therefore, slight difference between the data from 2D and 3D motion analysis system are expected. However, to our knowledge, it has not been yet estimated a threshold value which will be assumed as significant difference between the two motion analysis systems (2D-3D).

9 Conclusion

Within the clinical and research field, quantitative upper limb motion analysis is recognized as useful tool for assessing the recovery of upper limb function in stroke patients. Upper limb motion could be analyzed two dimensionally using low cost technology and three dimensionally using more expensive and complicating laboratories. In this study we evaluate the agreement between a portable single camera motion analysis system and the gold standard in 3D motion analysis, Vicon system. We showed that the video and Vicon system have an overall good agreement for both healthy and stroke patients in terms of trunk tilt during a reaching task. However, the results showed a significant variability in values of upper limb coordination in stroke patients, which could be well explained by the limitation of video system of single plane capturing. Therefore, the video analysis system may have the potential to objectively evaluate upper limb kinematics in healthy and stroke patients with slightly concern in connection with stroke patients with severe impairment. The relevance of this study lies on the findings that the 2D video can record the upper limb discoordination and the trunk compensation in stroke patients thereby detecting differences in motion between healthy and stroke surcivors. Nevertheless, due to the fact that the small sample size of the current study causes limitations in the predictions, future studies with larger sample size will be recommended for the validation of the 2D video analysis system in the assessment of upper limb motion in stroke patients.

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11 Appendix 1

Participant Information Sheet

Name of department: Biomedical Engineering

Title of the study: Validation of a single camera video system to measure upper limb motor control in stroke survivors

Short title: VAULTS (Video Analysis of Upper Limb Tests in Stroke Survivors)

Introduction

We are a group of researchers at the University of Strathclyde interested in stroke rehabilitation. This particular project is being led by Dr. Andy Kerr who is a research physiotherapist working in the Biomedical Engineering department (telephone: 0141 548 2855; email a.kerr@strath.ac.uk) with Professor Rowe and colleagues in the department of Electronic & Electrical Engineering**,** Drs. Vladmir and Lina Stankovic and Cheng Yang.

What is the purpose of this investigation?

Recovery of arm and hand function after a stroke is not great with many people left with little useful movement. We need to improve our understanding of how the arm and hand recovers after a stroke so we can devise more effective treatments. One of the barriers to improving our understanding is the use of basic methods for measuring the amount and quality of movement in the upper limb (arm and hand). At the University of Strathclyde we have developed a portable video system that can accurately and quickly measure movements of the whole upper limb and trunk. This can improve the amount of detailed information we can collect from stroke survivors participating in research studies as well as benefitting patients and therapists during rehabilitation sessions by providing detailed feedback. So far we have conducted tests on people without stroke and it has worked very well. Now we would like to make sure it works just as well with stroke survivors, in particular stroke survivors whose upper limb has been affected by their stroke but are still able to move their upper limb to some extent.

Do you have to take part?

We are looking for a small group (5-10) of people who have had a stroke affecting movement of their upper limb. Whether you take part or not is entirely your own decision. Your decision will not have any bearing on any of the health or social services you may be receiving. If you do decide to take part but later change your mind this is entirely up to you and this decision will not have any consequences for you.

What will you do in the project?

If you decide to take part in the study we will arrange a time for you to come to the University of Strathclyde for a two hour appointment. During this time we will use special cameras to record detailed movement of your arm and hand. We will ask you to carry out a number of movements but will allow you plenty of time to recover between movements should you get tired. We will only ask you to perform movements you are capable of performing since the purpose of this project is to make sure our system is good enough for stroke survivors and not to test your own ability. Unfortunately we are not able to provide payments for your time or reimburse any expenses you may have incurred using public transport or your own car. We can, however, transport you to and from the University at no cost, using the departmental car.

Why have you been invited to take part?

We are inviting people who have had a stroke affecting their upper limb (hand and arm), are able to follow simple instructions and can attend a two hour appointment at the University of Strathclyde during working hours in September 2013.For the test to work best we need individuals who are able to move their arm/hand, this might be very limited movement or it may be that you have almost normal movement. We are interested in testing our system across as many different people as possible so the amount of movement you have doesn't matter as long as you have some.

What are the potential risks to you in taking part?
We are confident that the study has few risks involved since we are only asking you to perform movements you might do in a routine exercise or therapy session. We will attach a few sticky markers to your skin during the test, occasionally this can cause a mild irritation similar to having sellotape attached to your skin. This should only be a temporary irritation since the markers will only be in place for around 40 minutes.

What happens to the information in the project?
We will use a unique code for each individual who participates in the study so all the information you provide and the results of the test, will be kept anonymous. We will ask you for information regarding you and your stroke, this will amount to questions about your age and how long it has been since your stroke. This information, along with the information from the cameras, will be stored in a locked cabinet in the department of Biomedical Engineering. The video clips we will take of your arm movements will not show your face and will be destroyed when we have analysed your movement, this will be on completion of the project i.e. September 2014, until that point the videos will be stored on an encrypted external hard drive which will be kept in a locked cabinet, in the department of Biomedical Engineering.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

What happens next?
If you are interested in participating in the study please contact Dr. Andy Kerr (a.kerr@strath.ac.uk or 0141 548 2855) and we will arrange a suitable time for you to come to the appointment at the University as well as answer any questions you may have and organise transport. If you have decided not to participate we would like to thank you for reading this information sheet and considering our research.

When we have finished collecting all the information we will analyse the results which will help us plan a larger study involving more stroke survivors. We will also send each participant a short summary of what we have found and will let colleagues from other universities know about our results during scientific conferences, the details of which may be published in scientific journals.

Researcher Contact Details:
Dr. Andy Kerr, Department of Biomedical Engineering, Wolfson Building, 106 Rottenrow, Glasgow G4 0NW

Telephone: 0141 548 2855

Email: a.kerr@strath.ac.uk

Chief Investigator Details:
Professor Philip Rowe, Department of Biomedical Engineering, Wolfson Building, 106 Rottenrow, Glasgow G4 0NW

Telephone: 0141 548 2855

Email: Philip.Rowe@strath.ac.uk

This investigation was granted ethical approval by the University of Strathclyde ethics committee.

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Secretary to the University Ethics Committee
Research & Knowledge Exchange Services
University of Strathclyde
Graham Hills Building
50 George Street
Glasgow
G1 1QE

Telephone: 0141 548 3707
Email: ethics@strath.ac.uk

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

Consent Form

Name of department: Biomedical Engineering

Title of the study: Validation of a single camera video system to measure upper limb motor control in stroke survivors

Short title: VAULTS (Video Analysis of Upper Limb Tests in Stroke Survivors)

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that I can withdraw my data from the study at any time.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project
- I consent to being video recorded as part of the project Yes/ No

In agreeing to participate in this investigation I am aware that I may be entitled to compensation for accidental bodily injury, including death or disease, arising out of the investigation without the need to prove fault. However, such compensation is subject to acceptance of the Conditions of Compensation, a copy of which is available on request.
Yes/ No]

(PRINT NAME)	Hereby agree to take part in the above project
Signature of Participant:	Date

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

12 Appendix 2

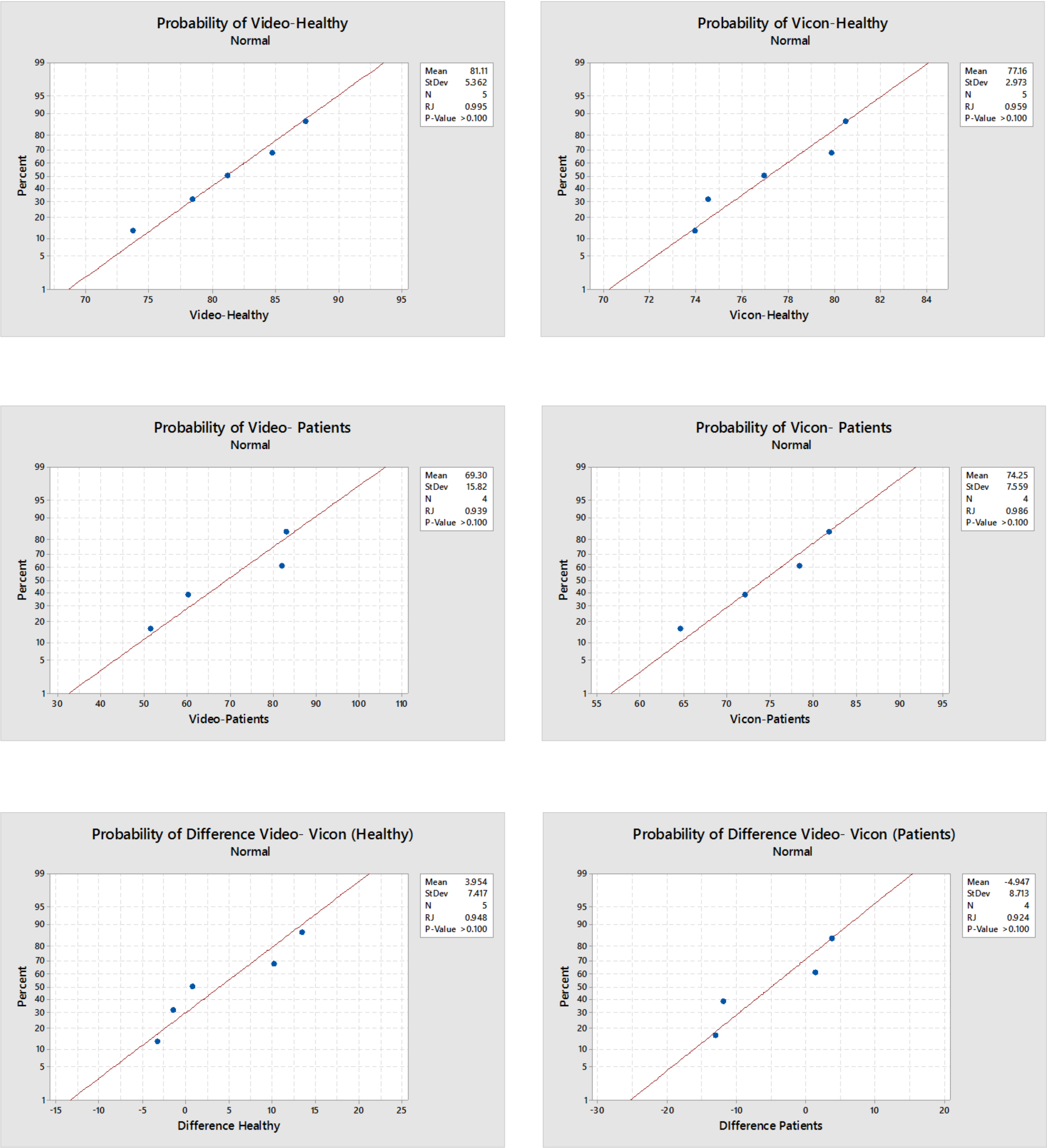

Figure 12-1: Ryan- Joiner Normality Test of Shoulder-Elbow Coordination

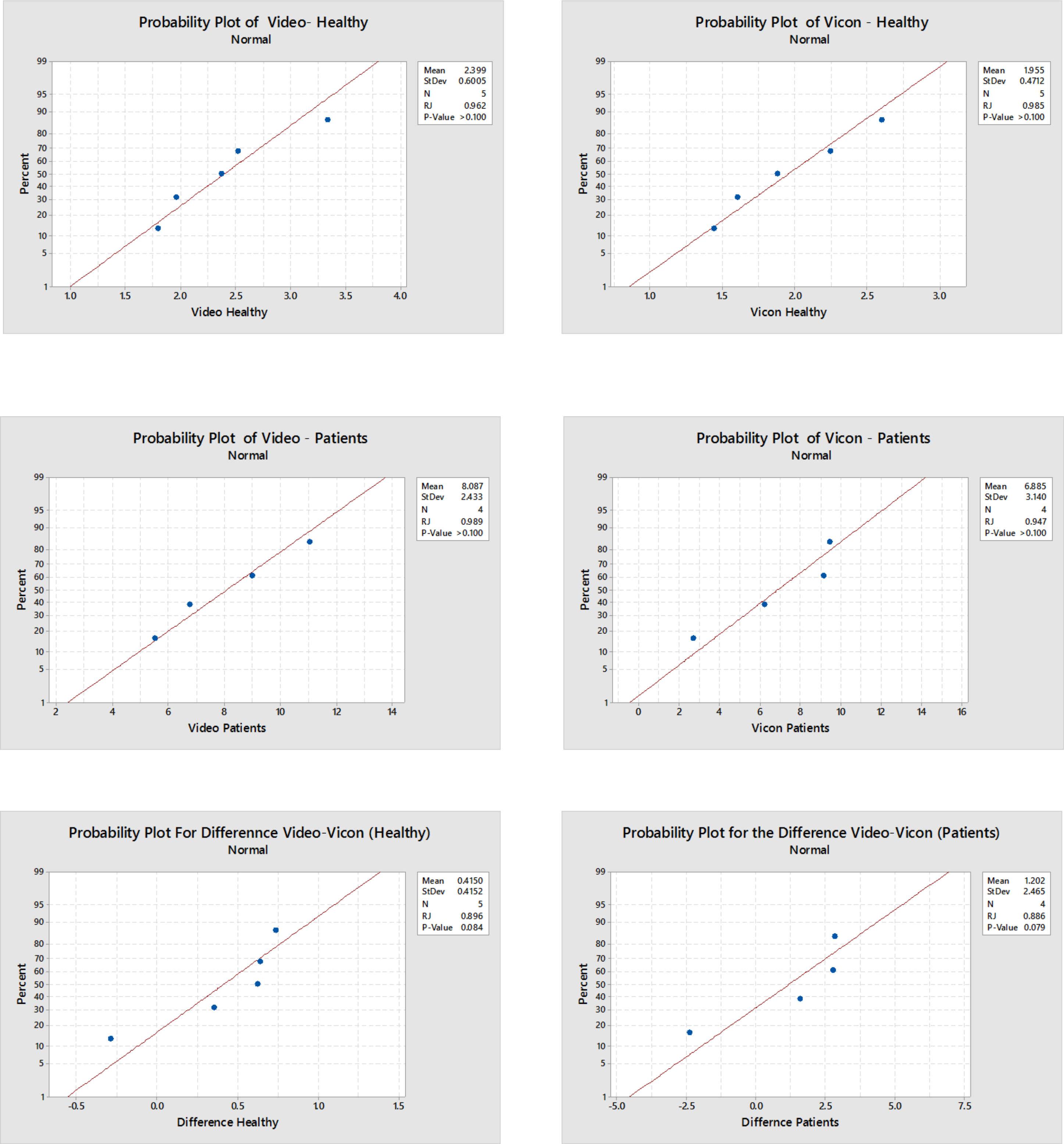

Figure 12-2: Ryan- Joiner Normality test of Trunk Tilt